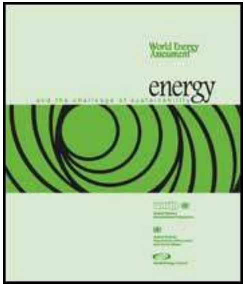

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PART II. ENERGY RESOURCES AND TECHNOLOGY OPTIONS

Chapter 5. Energy Resources

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ABSTRACT

A comprehensive account of the world's energy resource endowment is essential for any long-term energy assessment. Energy resources exist in different forms - some exist as stocks and so are exhaustible, others exist as flows and are inexhaustible, and a third form is based on exhaustible stocks that can be leveraged to resemble renewables. Most important, energy resources evolve dynamically as a function of human engineering ingenuity, driven by the desire to supply affordable and convenient energy services. Although the term stocks suggests finiteness (which is ultimately correct), the accessible portion depends on technology and on the future demand for that resource. Resources not demanded by the market are 'neutral stuff'. Demand plus advances in technology and knowledge turn neutral stuff into reserves that are replenished upon use by further advances in technology and knowledge, enabling humans to tap into resources previously beyond reach. But for stocks there will eventually be a limit. In contrast, resources based

on annually recurring flows are distinctly different from stocks: harvested prudently, they are renewable. But resources are not an end in themselves, and their attractiveness must be seen in the context of societies' energy service needs, of the technologies that convert resources into energy services, and of the economics associated with their use. This chapter assesses whether long-term energy resource availability could impede sustainable development and, based on a dynamic technology concept, provides a comprehensive account of the world's energy resource endowment.

This chapter reviews fossil, nuclear, and renewable energy resources. The reserve and resource volumes presented here cover the ranges considered robust by most of the lead authors. The main controversy yet to be resolved concerns the different views on the roles of technology and demand in the long-term availability of a particular resource. Subject to debate is the extent to which reserves can be converted from additional conventional resources with lower geological assurance and from unconventional resources lacking economic attractiveness given current markets and technologies. Natural flows are immense for renewable resources, but the level of their future use will depend on the technological and economic performance of technologies feeding on these flows as well as on possible constraints on their use. The long-term availability of energy resources will likely become more an issue of the degree to which future societies want to balance environmental and economic tradeoffs, control greenhouse gas emissions, and internalise externalities, or of the technological and economic performance of different clean energy conversion technologies, than a question of resource existence.

This chapter examines long-term energy resource availability primarily from the perspectives of theoretical maximums, or ultimately recoverable resources. Admittedly, it can be argued that an analysis based on ultimately recoverable resources is irrelevant - hydrocarbon occurrences or natural flows become resources only if there is demand for them and appropriate technology has been developed for their conversion and use. Indeed, energy resources generally should not be scrutinised without reference to the

chain extending from the extraction of resources to the supply of energy services - that is, along all the conversion steps to the point of what consumers really want: transportation, communication, air conditioning, and so on. But the assessment in this volume has been structured so that each link of the chain is explored separately. Energy conversion technologies are discussed in chapters 7 (renewable energy technologies) and 8 (advanced fossil and nuclear energy technologies), as well as in chapter 6 (energy efficiency).

Hydrocarbon occurrences become resources only if there is demand for them and appropriate technology has been developed for their conversion and use.

Definitions and units

A variety of terms are used to describe energy reserves, and different authors and institutions have different meanings for the same terms. Meanings also vary for different energy sources. The World Energy Council defines resources as "the occurrences of material in recognisable form" (WEC, 1998). For oil, it is essentially the amount of oil in the ground. Reserves represent a portion of resources and is the term used by the extraction industry. British Petroleum notes that proven reserves of oil are "generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions" (BP, 1999). Other common terms include probable reserves, indicated reserves, and inferred reserves - that is, hydrocarbon occurrences that do not meet the criteria of proven reserves. Undiscovered resources are what remains and, by definition, one can only speculate on their existence. Ultimately recoverable

resources are the sum of identified reserves and the possibly recoverable fraction of undiscovered resources and generally also include production to date. Then there is the difference between conventional and unconventional occurrences (oil shale, tar sands, coalbed methane, clathrates, uranium in black shale or dissolved in sea water), especially the rate at which unconventional resources can be converted into conventional reserves.

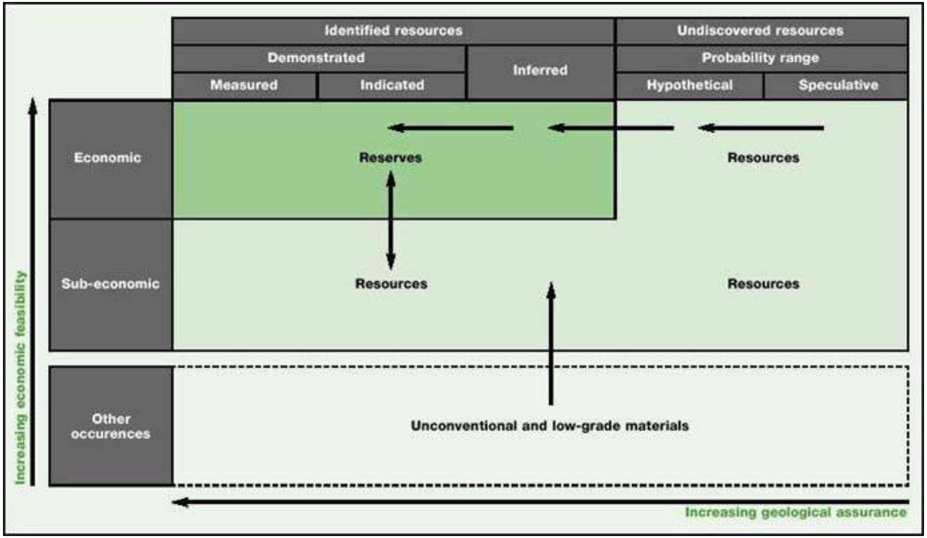


FIGURE 5.1. PRINCIPLES OF RESOURCE CLASSIFICATION

Source: Based on McKelvey, 1967.

To the extent possible, this chapter uses the McKelvey box, which presents resource categories in a matrix with increasing degrees of geological assurance and economic feasibility (figure 5.1). This scheme, developed by the U.S. Bureau of Mines and the U.S.

Geological Survey (USGS, 1980), is to some extent also reflected in the international classification system recently proposed by the United Nations.

In this classification system, resources are defined as concentrations of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form that economic extraction is potentially feasible. The geologic dimension is divided into identified and undiscovered resources. Identified resources are deposits that have known location, grade, quality, and quantity or that can be estimated from geologic evidence. Identified resources are further subdivided into demonstrated (measured plus indicated) and inferred resources, to reflect varying degrees of geological assurance. Reserves are identified resources that are economically recoverable at the time of assessment (see the British Petroleum definition, above).

Undiscovered resources are quantities expected or postulated to exist under analogous geologic conditions. Other occurrences are materials that are too low-grade or for other reasons not considered technically or economically extractable. For the most part, unconventional resources are included in ‘other occurrences’.

The boundary between reserves, resources, and occurrences is current or expected profitability of exploitation, governed by the ratio of market price to cost of production. Production costs of reserves are usually supported by actual production experience and feasibility analyses, while cost estimates for resources are often inferred from current production experience adjusted for specific geological and geographic conditions.

> Technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs.

For several reasons, reserve and resource quantities and related supply-cost curves are subject to continuous revision. Production inevitably depletes reserves and eventually exhausts deposits, while successful exploration and prospecting add new reserves and resources. Price increases and cost reductions expand reserves by moving resources into the reserve category and vice versa. The dynamic nature of the reserve-resource relationship is illustrated by the arrows in figure 5.1. Technology is the most important force in this process. Technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs.

The outer boundary of resources and the interface to other occurrences is less clearly defined and often subject to a much wider margin of interpretation and judgement. Other occurrences are not considered to have economic potential at the time of classification. But over the very long term, technological progress may upgrade significant portions to resources.

In 1992 the United Nations Economic Commission on Europe (UNECE) launched an effort to define a generally applicable resource classification scheme with a higher resolution of technical and economic feasibility than the McKelvey box. By adding a third dimension - the level of actual feasibility of extraction based on geological engineering assessments - this new classification provides a more accurate picture of the accessibility of resources. In 1997 the United Nations International Framework Classification for Reserves/Resources - Solid Fuels and Mineral Commodities (UNFC) was completed and recommended by the Economic and Social Council (ECOSOC) for world-wide application. But it will take time for the UNFC to be universally adopted by public and private institutions and for fossil reserves and resources to be consistently reported in compliance with the UNFC.

For renewable energy sources, the concepts of reserves, resources, and occurrences need to be modified. Renewables represent annual flows available, in principle, on an indefinite

sustainable basis. Fossil energy reserves and resources, although expanding over time, are fundamentally finite quantities. In this context the annual natural flows of solar, wind, hydro, and geothermal energy and quantities grown by nature in the form of biomass (often referred to as theoretical potentials) would correspond to occurrences. The concept of technical potentials can be used as a proxy for energy resources, while economic potentials correspond to reserves. The distinction between theoretical and technical potentials reflects the degree of use determined by thermodynamic or technological limitations without consideration of practical feasibility or costs. Thus the economic potential is the portion of the technical potential that could be used cost-effectively. In terms of reserves, resources, and occurrences of hydrocarbons, economic and technical potentials are dynamically moving targets in response to market conditions and technology availability and performance.

This chapter reports oil resources in gigatonnes (1 Gt = 10^9 tonnes) and exajoules (1 EJ = 10^{18} joules) using the energy equivalent of 42 gigajoules per tonne of oil equivalent (GJ per toe). Gas resources are reported in tera cubic metres (1 Tm^3 = 10^{12} cubic metres) and converted to EJ using 37 gigajoules per 1,000 cubic metres (GJ per 1,000 m^3). Coal resources are usually reported in natural units, although the energy content of coal may vary considerably within and between different coal categories. The Bundesanstalt fr Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, referred to here as the BGR) in Hannover (Germany) is the only institution that converts regional coal occurrences into tonnes of coal equivalent (1 tce = 29 gigajoules). Thus coal resource data come from the BGR. Uranium and other nuclear materials are usually reported in tonnes of metal. The thermal energy equivalent of 1 tonne of uranium in average once-through fuel cycles is about 589 terajoules (IPCC, 1996a).

Oil reserves and resources

Views on the long-term availability of oil and natural gas continue to spark controversy and debate. One school of thought believes that the best oil fields have already been discovered and that the amount of oil still to be discovered is somewhat limited. The other school regards oil reserves as a dynamic quantity, driven by demand and technological advances. The second school is more optimistic about future hydrocarbon availability.

Ultimately recoverable resources - the static or geologists' view

For many years, world oil reserves have experienced small but steady increases, which implies that the discovery or delineation of new reserves has at least kept pace with production. But many geologists focus on the concept of a quasi-fixed stock of hydrocarbon occurrences that, once production commences, can only decrease. For oil, they argue that few new oil fields have been discovered since the mid-1970s, and that most reserve increases have come from revisions of previously underestimated existing reserves (Hatfield, 1997; Campbell and Laherrere, 1998) and improved recovery techniques. Peak production lags behind peak discovery (of the mid-1960s) by several decades. Larger and more obvious fields are found first, leading to an early peak in discovery and diminishing returns in exploration: the more that is found, the less is left to find. Fields that are smaller and harder to find and to exploit follow, but eventually the fixed stock will be exhausted. Some 90 percent of current global oil production comes from fields more than 20 years old.

TABLE 5.1. ESTIMATED OIL RESERVES

Region	Identified reserves (Masters and others, 1994)		Identified reserves plus 95%[a] (Masters and others, 1994)		Identified reserves plus mode[b] (Masters and others, 1994)		Identified reserv plus 5%[c] (Maste and others, 1994	
	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajoules	Gigatonnes	Exajou
North	8.5	356	14.3	599	17.0	712	23.7	

America								
Latin America and Caribbean	17.3	724	22.6	946	26.2	1,097	41.6	1,
Western Europe	5.6	234	6.8	285	7.7	322	11.2	
Central and Eastern Europe	0.3	13	0.4	17	0.5	21	1.1	
Former Soviet Union	17.0	712	25.1	1,051	30.6	1,281	49.9	2,
Middle East and North Africa	87.6	3,668	97.0	4,061	104.6	4,379	126.4	5,
Sub-Saharan Africa	4.0	167	5.9	247	7.3	306	12.3	
Pacific Asia	3.1	130	4.1	172	4.8	201	7.3	
South Asia	1.0	42	1.1	46	1.3	54	1.8	
Centrally	5.1	214	7.8	327	9.8	410	17.9	

planned Asia								
Pacific OECD	0.4	17	0.6	25	0.7	29	1.3	
Total[e]	**150**	**6,277**	**186**	**7,776**	**210**	**8,812**	**295**	**12,32**

> **Note: Excludes cumulative production to the date of assessment. a. Identified reserves plus estimates of undiscovered resources with a 95 percent probability of discovery. b. Identified reserves plus estimates of undiscovered resources with a 50 percent probability of discovery. c. Identified reserves plus estimates of undiscovered resources with a 5 percent probability of discovery. d. Includes enhanced recovery of past and future oil production. e. Totals rounded.**

Cumulative production is a good proxy for geological knowledge gained through exploration experience. All these facts leave no room for any conclusion other than that peak production is being approached rapidly. In the 1960s ultimately recoverable resources became a popular concept for quantifying the fixed stock of hydrocarbon occurrences. Ultimately recoverable resources include cumulative production, proven reserves at the time of estimation, and oil remaining to be discovered - in other words, the ultimate oil wealth available to humans. For the past 40 years most estimates of ultimately recoverable resources for conventional oil have ranged from 200 - 400 gigatonnes. More recently, Campbell and Laherrere (1998) put ultimately recoverable reserves at about 250 gigatonnes, Hiller (1999) at 350 gigatonnes, Edwards (1997) at 385 gigatonnes, Masters and others (1994) at 281 - 390 gigatonnes, and Odell (1997) at 410 gigatonnes. All these estimates include production to the date of estimation (96 - 110 gigatonnes).

The debate on the size of ultimately recoverable resources and the time horizon when the depletion midpoint will be reached includes only conventional oil occurrences. Shale oil,

tar sands (natural bitumen), and heavy crude oil are considered unconventional oil resources, defined as occurrences that cannot be tapped with conventional production methods for technical or economic reasons or both (Rogner, 1997; Gregory and Rogner, 1998). These resources form a large part of the vast store of hydrocarbons in the Earth's crust and, in the case of oil, have been assessed to be at least as large as conventional oil resources (see below). The existence of unconventional oil and gas is acknowledged by 'fixed stock' analysts, but they are less sanguine about the future technological potential for bringing these resources to market. Technological pessimism and an exclusive focus on conventional oil largely explain the geologists' view that global oil production will reach its peak and mid-depletion point in the near future.

Conventional oil. Table 5.1 reports recent estimates, excluding cumulative production to date, of identified or proven oil reserves and natural gas liquids. All these estimates report reserves at around 1,000 billion barrels of oil (143 - 150 gigatonnes).

Masters and others (1994) estimate identified reserves on 1 January 1993 to be 150 gigatonnes (6,277 exajoules), only slightly higher than British Petroleum and World Energy Council estimates of proven reserves at the end of 1997.[1] Masters and others also estimate undiscovered oil resources based on a modified Delphi technique and geological analogies. Their low estimate (95 percent probability of discovery) brings their total for recoverable conventional oil reserves to 186 gigatonnes (7,771 exajoules). If cumulative production until 1994 of 95 gigatonnes (3,990 exajoules) is added, the total for ultimately recoverable resources is 281 gigatonnes (11,800 exajoules). The medium (mode) estimate of undiscovered resources brings total recoverable oil reserves to 210 gigatonnes (8,812 exajoules) and ultimately recoverable resources to 305 gigatonnes (12,810 exajoules). The high (5 percent probability) estimate of undiscovered resources brings total recoverable oil reserves to 295 gigatonnes (12,329 exajoules) and ultimately recoverable resources to 390 gigatonnes (16,380 exajoules).

TABLE 5.2. ESTIMATED UNCONVENTIONAL OIL RESERVES AND RESOURCES

Region	**Oil shale**							
	Identified resources(BGR, 1998)		**Total resources(BGR, 1998)**		**Proven recoverable and estimated additional reserves(WEC, 1998)**		**Oil in place(BGR 1998)**	
	Gigatonnes	**Exajoules**	**Gigatonnes**	**Exajoules**	**Gigatonnes**	**Exajoules**	**Gigatonnes**	**Exajou**
North America	1.1	48	351.6	14,767	217.0	9,114	15.7	
Latin America and Caribbean	0.3	14	19.4	814	9.6	405	229.3	9,
Western Europe	0.5	22	8.9	374	0.0	1	9.8	
Central and Eastern Europe	1.1	45	2.8	116	0.0	0	0.1	
Former Soviet Union	4.2	178	9.6	405	6.5	273	0.1	
Middle East and North	7.6	319	8.1	340	28.0	1,175	45.2	1,

Africa								
Sub-Saharan Africa	0.0	0	16.4	690	0.0	0	1.4	
Pacific Asia	1.0	40	1.0	40	1.7	71	1.1	
South Asia	0.0	0	0.0	0	0.0	0	1.0	
Centrally planned Asia	0.6	25	20.0	840	0.0	0	10.8	4
Pacific OECD	3.8	160	44.5	1,870	36.0	1,513	0.0	
Total	**20.3**	**851**	**482.3**	**20,256**	**298.9**	**12,552**	**314.5**	**13,2**

In its 1998 survey the World Energy Council reported proven recoverable oil reserves of 146 gigatonnes (6,126 exajoules) and estimates additional recoverable reserves (excluding speculative occurrences) of 28 gigatonnes (1,192 exajoules), for a total of 174 gigatonnes (7,318 exajoules). This compares well with the Masters and others estimate of identified reserves plus 95 percent probability of undiscovered resources of 186 gigatonnes. The oil reserve estimates in table 5.1 reflect the views of geologists on the availability of conventional oil and are consistent with the ultimately recoverable resource estimates presented earlier.

Today only about 35 percent of the oil in place is recovered by primary and secondary production methods. With enhanced oil recovery methods, this rate can be increased to as much as 65 percent of the original oil in place in a reservoir, though at higher extraction

costs (BGR, 1995). Thus the application of enhanced oil recovery methods in abandoned fields and new developments increases conventional oil resources.

Table 5.1 shows the potential resources resulting from the use of enhanced oil recovery techniques. Resources are calculated based on an average recovery rate of 35 percent achieved in historical production and used in the delineation of proven recoverable reserves, and an enhanced oil recovery rate of 15 percent, for an overall recovery rate of 50 percent.

Unconventional oil. The vast amounts of unconventional oil occurrences include oil shale, heavy crude oil, and tar sands. Unconventional oil is already economic to exploit in some places, so some is defined as reserves. Further development may depend on higher oil prices, technological developments, and long-term demand for liquid fuels. According to BGR (1998), reserves of unconventional oil could be as high as 245 gigatonnes, substantially exceeding proven reserves of conventional oil (table 5.2).

***Oil shale* is a sedimentary rock rich in organic matter containing more than 10 percent kerogen. It can be used directly as a fuel in power plants or processed to produce synthetic petroleum products. The kerogen content of oil shale varies widely. According to BGR (1995), only about 1 percent of world resources contains more than 100 litres of oil per cubic metre rock, while 85 percent have less than 40 litres per cubic metre.**

Data on oil shale resources are presented in table 5.2. The most recent BGR (1998) estimate of oil shale resources is 482 gigatonnes, down from 920 gigatonnes in the 1995 estimate. WEC (1998) estimates recoverable and estimated additional reserves at 299 gigatonnes. Major oil shale resources are in China, Estonia, the United States, Australia, and Jordan. The large regional differences between the BGR and WEC estimates are likely the result of different definitions.

Because of the high costs of mining and processing, oil shale is produced only in small

quantities in China and Estonia. Estonia is the only country with an economy dominated by oil shale as a source of energy and for more than 70 years has been the largest user of oil shale in power generation. Recent production totalled 20 million tonnes of oil shale a year (Hobbs, 1995).

Heavy crude oil **is defined as high-viscosity crude oil with a density equal to or less than 20° API (934 kilograms per cubic metre). Extra heavy oil is crude oil with a density equal to or less than 10° API (1,000 kilograms per cubic metre). Unlike tar sands, the viscosity of these hydrocarbons is below 10,000 millipoise (see below). Heavy oil is formed by the degradation of conventional oil in shallow reservoirs.**

Recent estimates of heavy oil resources are summarised in table 5.2. BGR (1995) estimates oil in place to be 315 gigatonnes. In BGR (1998), 33 of these are considered reserves and 77 are considered resources, for a total of 110 gigatonnes - well within the range of future potential recovery given by Meyer (1997). About half of heavy oil resources are in Venezuela; the former Soviet Union, Kuwait, Iraq, Mexico, and China account for most of the rest.

Meyer (1997) uses the term ***unproved reserves*** **because his estimates include some probable and possible reserves. Quantities stated under undiscovered potential recovery include all resources based on geological and engineering judgement, using a recovery factor of 10 percent.**

Some 8 percent of world oil production come from heavy oil reservoirs, with Venezuela, the United States, Canada, Iraq, Mexico, and the former Soviet Union being major producers (BGR, 1998). Due to the nature of heavy oil, enhanced oil recovery methods such as steam flooding and hot water, polymer, and carbon dioxide injection are generally required for its extraction.

Tar sands **(*natural bitumen*)** ***and extra heavy oil*** **are sands or sandstones that contain a**

large portion of tarry hydrocarbons with a viscosity exceeding 10,000 millipoise. They are formed by thermal metamorphism and biodegradation of conventional oil deposits. The high viscosity of these hydrocarbons requires unconventional extraction methods such as mining with bucket-wheel excavators or in truck and shovel operations. Natural bitumen typically contains large portions of sulphur and trace elements, including vanadium and nickel.

BGR (1998) estimates that 115 of the 658 gigatonnes of tar sands qualify as possible reserves (see table 5.2). Commercial production is limited to the Athabasca tar sand deposits of Alberta (Canada), with a volume of 25 million tonnes in 1998 (WEC, 1998). To reduce the environmental disturbance caused by surface mining, in situ techniques are increasingly used (box 5.1). In addition, new extraction technologies, such as steam-assisted gravity drainage, are being developed to reduce oil viscosity through steam injection (George, 1998). The use of extra heavy oil has commenced in the Orinoco oil belt of Venezuela (BGR, 1998).

Available resources - the dynamic or economists’ view

Unlike geologists, who tend to treat resources as an innate component of the physical world, economists view what exists in the Earth’s crust as ‘neutral stuff’ (Odell, 1998) that becomes a resource only if there is a market demand for it. Put differently, "there are huge amounts of hydrocarbons in the earth’s crust (Adelman and Lynch, 1997), and "estimates of declining reserves and production are incurably wrong because they treat as a quantity what is really a dynamic process driven by growing knowledge" (Nehring, 1998). Improvements in technology - such as three-dimensional seismic surveys and extended-reach drilling - have allowed higher recovery rates from existing reservoirs and the profitable development of fields once considered uneconomic or technically beyond reach, expanding the boundary of reserves and shifting resources into the reserve category.

BOX 5.1. ENVIRONMENTAL OBSTACLES TO EXTRACTING UNCONVENTIONAL OIL

The production of unconventional oil and the necessary upgrade to marketable fuels can hurt local environments. Mining, conversion, and upgrading to synthetic crude oil can produce toxic heavy metals and large quantities of solid and acidic liquid and gaseous wastes that need to be contained, cleaned, and disposed ofin an environmentally benign manner. This may require stringent environmental controls and new policies for toxic waste disposal. Extracting hydrocarbons from unconventional oils such as tar sands, heavy oils, and oil shale involves very large surface (open-pit or strip) mining and underground mining (room and pillar technique), steam soaking, steam flooding, or in situ combustion. Here the production of tar sand and its upgrading to synthetic crude oil are used to show the potential environmental constraints of large-scale unconventional oil production.

The production of synthetic crude oil from Alberta, Canada’s tar sand deposits involves open-pit mining and handling of 5 tonnes of tar sands and overburden per barrel of oil produced (Penner and others, 1982), milling to separate the bitumen from the sand, and upgrading it to commercial quality. Syncrude, a Canadian company, processes 510,000 tonnes of tar sands a day and recovers about one barrel of heavy oil for every 2 tonnes of tar sands processed (Stosur and others, 1998). A hot water process is the most common for extracting oil from the sand. The process is energy-intensive and requires large quantities of hot water. Syncrude operations require 1,400 tonnes an hour of water heated to nearly 500 degrees Celsius. Water is recycled to the maximum extent (90 percent). The remaining materials (tailings) after the bitumen has been extracted (extraction rate some 90 percent)are liquids and sand. Most of the tailings are the excavated overburden rock and rejected sand; both can be stockpiled and used as backfill with little threat to the environment (Stosur and others, 1998).

Things are different for the liquid tailings, which are contaminated with organic and inorganic compounds (sulphur, porphyrins, salts of organic acids) and can seriously damage nearby aquatic ecosystems. The liquid is stored in settling ponds, allowing water to clarify before it is recycled.

These ponds are designed as ‘zero discharge’ basins, and no process-affected water is discharged in running waters. But while tailings sand settles out quickly, the fine-grained materials (silts and clays) and residual bitumen consolidate slowly and can pose a long-term problem and liability. Tailings ponds must be constructed to last several decades and must be guarded against erosion, breaching, and foundation creep until better disposal practices become available (Stosur and others, 1998). New processes such as dry retorting - which generates dry tailings - are expected to minimise the risk of acid drainage from tar sand tailings. Other methods include faster consolidation of fine tailings, detoxification of tailing pond water, and reprocessing of fine tailings (including co-production of minerals and metals).

Spent tar sand (mainly sand, silt, and clay contaminated with the remaining bitumen and caustic compounds) is put in specially designed storage areas to avoid acid drainage or used as fill material in mine reclamation efforts. While the disrupted land area can be considerable, land reclamation is usually imposed on mine operators to limit permanent environmental damage and to return land to a stable, biologically self-sustaining state.

Upgrading operations are the primary source of airborne emissions. Sulphur dioxide, particulates, hydrocarbons, vanadium, and nickel were originally of major concern. In addition, bitumen contains several carcinogenic polycyclic aromatic hydrocarbons (WHO, 1982). Hydrotreaters remove sulphur and nitrogen and produce elemental sulphur as a by-product. Nitrogen is removed as ammonia and used as an under-boiler fuel or for chemical feedstock. Hydrogen sulphide is removed from the by-product fuel gas that fuels parts of the upgrading operations. The synthetic crude oil produced from Alberta’s tar sand deposits is 32 - 33^{o} API with 0.1 - 0.2 percent sulphur. It contains no residue, while typical conventional crudes have about 8 percent residue.

Stosur and others (1998) estimate that only 15 percent of tar sand resources are suitable for surface mining. The rest would have to be extracted by in situ methods, which minimise land disturbance through multiwell pads and horizontal drilling (Sadler and Houlihan, 1998). To reduce odour and greenhouse gas emissions, care must be taken to collect and reuse or flare the gases generated by the process.

Alberta’s tar sand operations indicate that environmental protection is the result of effective environmental regulation and controls, including a balance of resource development and resource conservation and of environmental and socioeconomic policies.

In addition, economists argue, a distinction between conventional and unconventional occurrences is irrelevant. Today most unconventional occurrences are neutral stuff and will become resources and reserves if there is sufficient demand. In fact, certain unconventional occurrences - heavy oil, tar sands, coalbed methane and gas from aquifers - have already started to ‘come in from the margin’. Conventional discoveries previously regarded as uneconomic can now be developed profitably, and recoverable reserves can be increased in fields being developed or under production. In short, economists view oil and gas reserves as a portion of the total hydrocarbon occurrences contained in the Earth’s crust, where volumes depend on exploration know-how to locate and evaluate a play (delineated deposit) and on the capability of technology to extract it at an acceptable cost given sufficient demand.

The question of long-term hydrocarbon resource availability, then, is viewed from the perspective of anticipated demand in competitive markets - taking into account technological change and growing knowledge. In the presence of sufficiently large conventional oil reserves there is, at present, no demand for the large-scale use of abundant unconventional oil occurrences (see above). This explains the absence of any significant motivation for a comprehensive and systematic evaluation of these resources or for the development of technology for their economic and environmentally acceptable recovery.

Economists take proven conventional oil reserves of 150 gigatonnes as a point of departure that, based on their definition, can be brought to the market at post-1986 price

levels. In addition, economists point to industry expectations that proven reserves will grow 50-70 gigatonnes by 2020 (Shell, 1996). They point out that the oil industry has historically responded to demand by finding and developing reserves, even given the long lead time for this process: since World War II it has taken more than 40 years to move from identifying reserves to producing resources. This is seen as a clear indication that the process of stock replenishment is working effectively.

A bigger role for unconventional oil. Economists also argue that unconventional oil should be viewed as an important element of the oil resource base - and after 2030 it will be a critical complement to conventional oil production in keeping the oil supply curve moving upwards. This long process of the changing supply pattern will be seamless from the viewpoint of oil producers. From the point of view of users the process will be unimportant, because no essential difference will arise for them merely because of the changing nature of exploitation of oil habitats in the Earth's surface. In precisely the same way, today's oil consumers do not need to consider whether their supply is from shallow or deep horizons, or from onshore or offshore locations.

> The oil industry has historically responded to demand by finding and developing reserves, even given the long lead time for this process.

The ultimate resource base of unconventional oil is irrelevant to the 21st century's energy supply. Occurrences of such oil that are already known and under exploitation can provide the global supply likely to be required in the 21st century. On the other hand, economic or environmental considerations - or both - could convert unconventional resources back to neutral stuff, as has occurred in recent decades with previously designated coal resources.

Costs and technological developments. New technologies for exploring and extracting oil have lowered exploration, development, and production costs while expanding the oil resource base. Further advances in technology must also be expected, resulting in additional reductions in cost. Part of these productivity gains will be offset by the use of more remote, harder-to-access, and smaller deposits. Still, it appears plausible that technological progress will continue to keep production costs in check.[2] The technology learning curve for synthetic crude oil production from tar sands in Alberta is a good example of the impact of technology on production costs. In 1978 a barrel of synthetic crude oil cost about $26 a barrel. By 1996 breakthroughs in the technology for producing and refining bitumen as well as better operating procedures had lowered these costs to $9.60 a barrel (Polikar and Cyr, 1998).

Two developments will likely put upward pressure on prices. The first is the increasing volume of energy that will be demanded in the first half of the 21st century. The second is the significantly increased cash flows required by the international oil industry to sustain enhanced investment in the initial large-scale exploitation of rapidly increasing volumes of unconventional oil and gas. In the 1950s the ability of consumers to secure large volumes of international oil depended on the super-normal profits that the industry was able to generate. More recent breakthroughs for gas in Europe and elsewhere were likewise achieved because of super-normal profitability in the industry. After 2030, following the introduction to global markets of large-scale unconventional hydrocarbons, prices should fall back as the long-run supply prices of the two commodities once again start to decline under conditions of advancing technology and increasing economies of scale (Odell, 1998).

Reconciling the two views

The differences between geologists’ (static) and economists’ (dynamic) views of oil resources can be partly explained by the way the different schools view unconventional

oil. Geologists draw a strict line between conventional oil (the oil they look for) and unconventional oil (the oil that does not fit their template). Although some unconventional oil is being exploited economically, geologists take a conservative view of its long-term commercial viability. In contrast, economists consider irrelevant the dividing line between conventional and unconventional oil. They anticipate a seamless transition from one to the other as long as demand and market prices allow for a profitable return on investment. In that case, unconventional occurrences estimated to exist in the Earth's crust (see table 5.2) would extend the oil age well beyond the mid-21st century. Without demand, the issue of resource availability becomes meaningless and unconventional oil occurrences remain neutral stuff.

A historical review of the most popular guideline for the industry, the ratio of reserves to production, puts into perspective the two schools of thought. This ratio compares known reserves and current production and so measures the temporal reach of exhaustible energy reserves. These ratios typically fluctuate between 20 and 40 years.

But the notion of a reserve-to-production ratio is seriously flawed and, in the past, has led to aberrant conclusions (MacKenzie, 1996). The most erroneous conclusion is that the world will be running out of reserves by the time suggested by the ratio.[3] For oil, ratios of 20 - 40 years have existed since the early 20th century (figure 5.2). According to this ratio, the world should have run out of oil a long time ago. Instead, driven by economics (in essence, demand for oil), advances in geoscience, and technological progress in upstream production, reserves have been continuously replenished from previously unknown sources (new discoveries) or technologically or economically inaccessible occurrences. Although reserve additions have shifted to more difficult and potentially more costly locations, technological progress has outbalanced potentially diminishing returns.

FIGURE 5.2. RATIO OF RESERVES TO PRODUCTION FOR CONVENTIONAL CRUDE OIL, 1900 - 98

Source: Adapted from BP, 1998.

New technologies for exploring and extracting oil have lowered exploration, development, and production costs while expanding the oil resource base.

Gas reserves and resources

Unlike oil, gas is not subject to controversy on estimates of ultimately recoverable reserves. Proven reserves are comparable to those of oil but high relative to current and cumulative production. Still, natural gas is often viewed as the poor stepsister of oil. The development of natural gas fields requires large investments in transmission and distribution infrastructure.[4] As a result gas discoveries, especially in developing countries,

are often not reported. But this does not imply a lack of gas occurrence - in fact, over the 21st century there is enormous potential for major gas discoveries.

Conventional gas

The most recent estimates of conventional gas reserves come from WEC (1998) for the end of 1996 and BP (1998) for the end of 1998. WEC gives total reserves as 177 Tm^3 (6,534 exajoules) at the end of 1996, 147 Tm^3 (5,450 exajoules) of which were proven recoverable reserves (table 5.3). The rest were additional recoverable reserves. The International Gas Union (IGU, 2000) reports total potentially recoverable reserves as high as 502 Tm^3 (18,390 exajoules).

Reserves have generally increased from survey to survey, reflecting dramatic changes in the economics of gas exploration and recovery. Reservoirs are being added in areas previously thought to have been exhausted, and new reservoirs that were previously overlooked or ignored are now being developed. Over the past 10 years reserve additions averaged 3.7 Tm^3 (134 exajoules) a year, much higher than the 1997 production of 2.2 Tm^3. Ivanhoe and Leckie (1993) note that fewer gas than oil fields are reported in developing regions, probably because gas has a lower economic and utility value, not because there are fewer gas fields.

Enhanced gas recovery using advanced recovery methods - notably hydraulic fracturing aimed at improving the permeability of reservoir rock - can substantially increase natural gas recovery in abandoned fields and newly developed reservoirs. Another, more innovative technique, horizontal air drilling, can also increase gas recovery in depleted gas zones (Elrod, 1997).

Estimates of potential reserves of natural gas resulting from enhanced gas recovery are

based on a historical average gas recovery rate of 50 percent and an enhanced recovery rate of 30 percent, for a total recovery factor of 80 percent. Schollnberger (1998) uses similar assumptions in an assessment of possible reserve development through 2100. Global cumulative natural gas production through 1998 totalled 62 Tm^3 (2,276 exajoules). Applying an average recovery factor of 50 percent leads to an original amount of 124 Tm^3. Enhanced gas recovery of 30 percent then enlarges reserves by 37 Tm^3. Likewise, enhanced gas recovery reserves from future production are estimated at 106 Tm^3 using WEC (1998) total recoverable reserves of 177 Tm^3 (see table 5.3). Thus total potential natural gas reserves available from enhanced oil recovery methods are estimated at 143 Tm^3 (5,290 exajoules), an amount only slightly lower than proven natural gas reserves and almost identical to the potential crude oil reserves expected from enhanced recovery methods.

Unconventional gas

BGR (1995) defines unconventional gas as natural gas derived from reservoirs not exploitable by conventional recovery techniques. Unconventional gas types include coalbed methane, tight formation gas, gas hydrates (clathrates), and aquifer (geopressured) gas. Regional estimates of unconventional gas occurrences in place are provided in table 5.4. The total resource potential exceeds 25,000 Tm^3 (960,000 exajoules).

Coalbed methane. Coalbed methane is a natural gas mixture containing more than 90 percent methane. It occurs primarily in high-rank coal seams from where it can migrate into the surrounding rock strata. Methane contents in coal seams can range from traces to 25 cubic metres per tonne of coal (Davidson, 1995). Regional resources of coalbed methane are genetically associated with the geographic distribution of bituminous coal

and anthracite deposits. The former Soviet Union accounts for nearly 50 percent of recoverable resources, centrally planned Asia (including China) has about 20 percent, and North America has 15 percent.

Coalbed methane can be a by-product of underground coal mining or be produced for the methane exclusively. In fact, coalbed methane is an explosive hazard in underground mining operations and for safety reasons has traditionally been vented with mines' fresh air circulation. Since the 1970s methane captured from underground mining has increasingly been used to supplement local gas supplies. Thus methane capture and use can significantly mitigate greenhouse gas emissions because it avoids the release of methane - a potent greenhouse gas - and may replace fossil fuels with a higher carbon content. For long-term and stable methane supplies from coalbeds, however, dedicated drilling in coalbeds is more important than the methane from active underground coal mines.

Commercial coalbed methane production occurs only in the United States, contributing about 5 percent to natural gas production (BGR, 1998). But pilot projects are under way in a number of other countries, including Australia, China, India, Poland, Russia, Ukraine, and the United Kingdom. Estimates of methane resources range from 85 - 262 Tm^3 (BGR, 1995, 1998; Rice, Law, and Clayton, 1993). This assessment uses the BGR (1995) estimate of 233 Tm^3 (see table 5.4).

Tight formation gas. Tight formation gas is natural gas trapped in low-permeability reservoirs with in situ permeability of less than 0.1 millidarcy (mD), regardless of the type of the reservoir rock (Law and Spencer, 1993). Production of tight gas requires artificial stimulation techniques - such as massive hydraulic fracturing - to improve reservoir permeability. An advanced technique is horizontal drilling to develop tight gas formations, often in combination with massive hydraulic fracturing. These stimulation methods can achieve gas flow rates two to three times those of conventional vertical wells. In recent

years about 3 percent of natural gas production has come from tight gas reservoirs.

TABLE 5.3. ESTIMATED NATURAL GAS RESERVES

Region	Proven recoverable reserves(WEC, 1998)		Total recoverable reserves(WEC, 1998)		Proven and additional reserves(IGU, 2000)		Proven reserves(BP, 1999)		Enhanced gas recovery	
	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3	Exajoules	Tm^3
North America	252	6.8	389	10.5	2,307	63.0	244	6.6	884	23.9
Latin America and Caribbean	303	8.2	426	11.5	1,556	42.5	298	8.0	306	8.3
Western Europe	181	4.9	300	8.1	436	11.9	177	4.8	306	8.3
Central and Eastern Europe	26	0.7	26	0.7	77	2.1	17	0.5	45	1.2
Former Soviet Union	2,087	56.4	2,583	69.8	5,767	157.5	2,112	56.7	1,923	52.0
Middle East and	2,076	56.1	2,250	60.8	5,343	149.5	2,065	55.4	1,421	38.4

North Africa										
Sub-Saharan Africa	155	4.2	155	4.2	238	6.5	161	4.3	93	2.5
Pacific Asia	207	5.6	207	5.6	798	21.8	196	5.3	158	4.3
South Asia	63	1.7	63	1.7	377	10.3	54	1.5	50	1.4
Centrally planned Asia	48	1.3	48	1.3	641	17.5	82	2.2	41	1.1
Pacific OECD	56	1.5	89	2.4	850	23.2	47	1.3	62	1.7
Total	**5,450**	**147.3**	**6,534**	**176.6**	**18,390**	**502.2**	**5,454**	**146.4**	**5,290**	**143.0**

TABLE 5.4. ESTIMATED UNCONVENTIONAL NATURAL GAS RESOURCE POTENTIAL IN PLACE

Region	**Coalbed methane**		**Tight formation gas**		**Gas hydrates**		**Geopressured gas**		**Total unconventional gas**	
	Exajoules	**Tm^3**	**Exajoules**	**Tm^3**	**Exajoules**	**Tm^3**	**Exajoules**	**Tm^3**	**Exajoules**	**Tm^3**
North America	2,898	78	518	14	80,575	2,178	109,964	2,972	193,955	5,242
Latin America	0	0	222	6	57,331	1,549	103,341	2,793	160,894	4,348

and Caribbean										
Western Europe	168	5	222	6	19,806	535	27,861	753	48,057	1,299
Central and Eastern Europe	126	3	37	1	0	0	6,623	179	6,786	183
Former Soviet Union	2,646	72	1,665	45	151,533	4,095	73,667	1,991	229,511	6,203
Middle East and North Africa	0	0	925	25	4,788	129	67,784	1,832	73,497	1,986
Sub-Saharan Africa	42	1	111	3	4,788	129	63,677	1,721	68,618	1,854
Pacific Asia	210	6	148	4	0	0	45,103	1,219	45,461	1,229
South Asia	42	1	37	1	4,788	129	17,427	471	22,294	602
Centrally planned Asia	2,058	56	333	9	0	0	27,824	752	30,215	817
Pacific	420	11	37	1	23,857	645	56,166	1,518	80,480	2,175

OECD										
Total	**8,610**	**233**	**4,255**	**114**	**347,467**	**9,391**	**599,437**	**16,201**	**959,769**	**25,940**

Source: BGR, 1995, 1998; Rogner, 1997.

Although tight gas reservoirs exist in many regions, only the tight gas resources in the United States have been assessed. The U.S. potential of tight gas resources from tight sandstone and Devonian shale reservoirs is 13.4 Tm^3 (BGR, 1995). BGR (1998) applies these U.S. estimates to extrapolate tight gas resource potential for other countries and regions, arriving at a global potential of 114 Tm^3 (see table 5.4).

Gas hydrates. IGU (1997) includes some unconventional gas in its definition of additional recoverable reserves - those that are at least of foreseeable economic interest and that may prove technically and economically recoverable with a reasonable level of confidence. This definition appears to exclude gas hydrates (clathrates). IGU (1997) notes that:

> **Current scientific inquiries around the world are considering gas hydrates as a potential future supply of natural gas. The hydrates are frozen ice-like deposits that probably cover a significant portion of the ocean floor. The extent of their coverage and the high methane content of gas hydrates motivate speculation about the gigantic quantities of methane that could become available. At the present time there has been no attractive proposal for a technique to allow this methane to be recovered. Nor has there been any scientific confirmation of the quantities of methane that might be involved. Nevertheless, such investigations might bear fruit at some stage and radically alter current ideas regarding natural gas availability.**

The existence of gas hydrates has been confirmed by direct evidence through sampling and by indirect evidence through geochemical and geophysical investigations. Samples have been recovered in 14 parts of the world; indirect evidence has been found in 30

others. Many oceanic occurrences have been inferred based on a special geophysical exploration technique - bottom-stimulating reflection. Resource estimates for gas hydrates are highly uncertain. BGR (1998) reports global clathrate occurrences of more than 9,000 Tm^3 (see table 5.4). Other estimates report clathrates as high as 20,000 Tm^3 (MacDonald, 1990a, b; Collet, 1993).

There are no economically attractive technological proposals for recovering methane hydrates (box 5.2). But given their enormous resource potential, it is plausible to expect that extraction methods will eventually be developed if long-term global gas demand warrants clathrate recovery. Research projects are under way in India, Japan, and the United States to examine the viability of gas hydrate recovery (Collet and Kuuskraa, 1998; BGR, 1998).

Aquifer (geopressured) gas. In many parts of the world, natural gas is found dissolved in aquifers under normal hydrostatic pressure, primarily in the form of methane (Marsden, 1993). This unconventional gas is also referred to as hydropressured gas or brine gas. The amount of gas dissolved in underground liquids increases substantially with depth. At depths up to 4,000 metres, 0.5 - 1.5 cubic metre of gas is dissolved per metre of water in aquifers. This gas factor jumps to 7 - 20 at depths of 7,000 - 8,000 metres (BGR, 1995).

Aquifer gas is expected to occur in nearly all sedimentary basins (Marsden, 1993). While no detailed assessment of aquifer gas resources is available, BGR (1998) derives potential aquifer gas in place from the groundwater volume contained in high-permeability sand stones in the hydrosphere. This approach leads to an estimate of 2,400 - 30,000 Tm^3 of geopressured gas in place, with a mean estimate of 16,200 Tm^3. In the absence of a more detailed assessment, a practical approach had to be taken in delineating regional resource quantities. The regional breakdown in table 5.4 was obtained by weighting the global mean estimate of gas occurrence in place with regional shares of total sedimentary area.

While these estimates of aquifer gas occurrences are highly speculative, the potential quantities are staggering. Even a future recovery factor of 5 percent implies a resource volume five times the conventional reserves estimates of BP. Aquifer gas is already produced in small quantities from shallow reservoirs in Italy, Japan, and the United States. But in all cases aquifer gas recovery has been motivated by the production of trace elements (such as iodine) rather than by the gas itself.

Coal reserves and resources

Coal deposits can be found in sedimentary basins of various geological ages. Mineable coal deposits require a minimum seam thickness over a sufficiently large area. Coal production occurs in open-pit extraction or underground mining. Coal resource estimates are generally based on drill-hole tests and geological observations. Coal is subdivided into several broadly defined types according to their caloric values. Generally, the types are bituminous coal (including anthracite), sub-bituminous coal, and lignite. For practical purposes, the subdivision is based on energy content, with the value of 16,500 kilojoules per kilogram as demarcation between hard coal (bituminous and high-energy sub-bituminous coals) and soft brown coal (lignite and low-energy sub-bituminous coals).

For almost 200 years coal has provided the basis for energy production as well as iron and steel manufacturing. It also fuelled the industrial revolution of the 19th century. In the 20th century - mainly after World War II - coal lost its leading position to crude oil. But the welfare and economic development of many countries continue to be based on coal. Coal provides about 22 percent of the world energy supply and is the most important fuel for electricity generation. About 40 percent of global electricity is produced in coal-fuelled power stations.

The differences between static and dynamic views of oil resources can be partly explained by the way the different schools view unconventional oil.

Coal will likely contribute substantially to the future world energy supply. Assuming no intervention policies targeted at preventing climate change, projections by IEA (1998c) and Nakicenovic, Grbler, and McDonald (1998) show global coal production increasing from 2.4 gigatonnes of oil equivalent (Gtoe) in 1995 to 4.0 Gtoe by 2020. Given its enormous proven reserves, the current rate of coal production could continue well into the future.

The size of coal resources is not a restraining factor to its use throughout the 21st century. Rather, continued coal use will depend on the timely development of production facilities and related infrastructure, given lead times of up to five years for open-cast operations and drift mines. Nevertheless, there is considerable potential for a significant increase in coal production capacity in the short to medium term. Although environmental considerations may limit coal use with current combustion technologies, advanced conversion technology - with carbon abatement and disposal - may create new market opportunities (see chapter 8).

Current resources and reserves

World coal resources in place are estimated at more than 7,400 billion tonnes of coal, or about 4,470 Gtoe (WEC 1998). The recoverable portion is estimated at roughly 500 Gtoe, which corresponds to the amount generally labelled reserves. About 85 percent of the resources in place are classified as bituminous or sub-bituminous (hard) coal; the rest is lignite (soft brown) coal. (Similar proportions apply to reserves.)

BOX 5.2. ARE GAS HYDRATES AN EXPLOITABLE ENERGY RESOURCE?

A gas hydrate is a crystalline cage of water molecules that can trap various gases. Hydrates can form under conditions of high pressure and low temperatures. Methane hydrates exist in polar permafrost and in sediments below the ocean floor where conditions are appropriate. Hydrates will not exist below a depth where the reservoir temperature is too high for their stability. But solid hydrate layers can provide top seals for reservoirs of free methane that can accumulate beneath. Offshore methane hydrate deposits have been identified near the coasts of many countries - including countries (such as Japan) otherwise poor in fossil fuels.

The amount of methane associated with hydrates is highly uncertain, but the quantities are probably far greater than conventional oil and gas resources combined. Estimates of global methane hydrate resources range from 0.1 - 300 million exajoules (Collet and Kuuskraa, 1998; Max, Pellanbarg, and Hurdle, 1997). How much can be practically and affordably recovered is also highly uncertain (USDOE, 1998). An emerging view is that free gas trapped beneath solid hydrate layers will be easier to recover than gas in hydrates (Max, Pellanbarg, and Hurdle, 1997). Free gas recovery would depressurise the reservoir, leading to hydrate melting at the hydrate - free gas interface and thus to free gas replenishment. The process could continue as long as the hydrate layer remains thick enough to cap the free gas below. Preliminary (though dated) estimates for recovering methane at favourable sites suggest that it might not be significantly more costly than recovering conventional natural gas (Holder, Kamath, and Godbole, 1984). But even if this proves accurate, getting the gas to major markets could often be quite costly because of high transport costs, since hydrate deposits are often far from such markets.

Three-quarters of global coal reserves are in Australia, China, India, South Africa, and the United States. Among regions, North America has the largest coal reserves (table 5.5). Substantial reserves are also available in the former Soviet Union and in South Asia. The European share has to be viewed with caution because reserves may soon be declassified to resources (neutral stuff) as production subsidies are eliminated and industry begins to close unprofitable operations.

In 1997 global coal production totalled 2,310 Gtoe, 91 percent of which was hard coal. China was the largest producer of hard coal (31 percent of the world total), followed by the United States (26 percent), India (7 percent), Australia (6 percent), and South Africa (6 percent). All other producers hold shares of less than 5 percent.

Almost 90 percent of world coal production is used domestically. In 1997 the 10 largest coal exporters traded about 500 million tonnes of hard coal. The largest exporter was Australia with a traded share of about 30 percent, followed by the United States with 15 percent.

TABLE 5.5. ESTIMATED COAL RESERVES (MILLIONS OF TONNES)

Region	Bituminous (incl. anthracite)	Sub-bituminous	Lignite	Total (exajoules)
North America	115,600	103,300	36,200	6,065
Latin America and Caribbean	8,700	13,900	200	533
Western Europe	26,300	600	47,700	1,178
Central and Eastern Europe	15,400	5,500	10,700	744
Former Soviet Union	97,500	113,500	36,700	4,981
Middle East and North Africa	200	20	0	6
Sub-Saharan Africa	61,000	200	< 100	1,465
Pacific Asia	900	1,600	5,100	10
South Asia	72,800	3,000	2,000	1,611
Centrally planned Asia	62,700	34,000	18,600	2,344

Pacific OECD	48,100	2,000	41,600	1,729
Total	**509,200**	**277,600**	**198,900**	**20,666**

Source: WEC, 1998.

Projections show global coal production increasing from 2.4 Gtoe in 1995 to 4.0 Gtoe by 2020.

Additional resources

WEC (1998) also provides information on coal resources by type. But because of incomplete country coverage, no regional or global aggregates are given. BGR (1995) estimated global coal resources at 5,000 Gtoe, of which 4,600 Gtoe are hard coal. In a 1998 update, BGR revised the estimate for additional coal resources in place to 4,300 Gtoe billion, of which about 3,500 Gtoe are additional hard coal resources. The Russian Federation has the largest share - about 2,100 Gtoe of hard coal. About 80 percent of the additional resources in the Russian Federation are in remote areas of Siberia. Large investments for infrastructure and development limit the conversion of these resources into reserves. Because of the large reserves, there is no immediate need for additional investigation of the resource potential world-wide. Estimates of the regional distribution of world total resources (including reserves) are shown in table 5.6.

Summary of fossil resources

Fossil fuel reserves, resources, and additional occurrences are shown relative to

cumulative consumption and current (1998) use in table 5.7. For an analysis that extends well into the 21st century and explores the long-term availability of fossil resources, the fossil resource base is the relevant yardstick. The resource base for conventional and unconventional oil and gas is large enough to last comfortably for another 50 - 100 years - and possibly much longer - essentially at prices not much different from today. This projection assumes that past hydrocarbon productivity gains in the upstream sector can be maintained and that these resources remain in demand.

Tapping into the vast fossil resource base may eventually become a transportation challenge. For one thing, fossil resources are not evenly distributed around the globe. For another, the location of many unconventional oil and, more important, gas occurrences is far from the centres of energy demand. In China and India coal delivery costs (for rail transport) already approach production costs. Transportation logistics and costs may affect the economic attractiveness of remote resource sites. Long-distance and trans-boundary energy transport raises concerns about the security of energy supply (see chapter 4).

The fossil resource data in table 5.7 are also shown in terms of their carbon content. Since the onset of the industrial revolution, 296 gigatonnes of carbon contained in fossil fuels have been oxidised and released to the atmosphere. The resource base represents a carbon volume of some 6,500 gigatonnes of carbon. The 296 gigatonnes of carbon emitted to the atmosphere already raise concerns about climate stability - and humankind has the means to add several times that amount during the 21st century. Fossil resource scarcity will not come to the rescue. Nakicenovic, Grbler, and McDonald (1998) indicate that between 1990 and 2100 emissions under the A2 scenario (see chapter 9) of some 1,600 gigatonnes of carbon - roughly the carbon content of conventional fossil reserves (see table 5.7) - could raise the atmospheric concentration of carbon dioxide to 750 parts per million by volume (ppmv). (Before the industrial revolution, carbon dioxide concentrations were 280 ppmv; today they are 360 ppmv.) The corresponding increase in global mean

temperature could be 2.0-4.5 Kelvin.[5]

Since 1973 the tradable price of oil (the ‘marker’ for competing fuels) has been much higher than the marginal cost of the highest-cost producer, reflecting geopolitics and a lack of competing fuels. Today the highest marginal cost of production is less than $10 a barrel - and in the Gulf it is just $2-3 a barrel (Rogner, 1997; Odell, 1998). Economic rent accounts for the rest of the tradable price. This rent could be reduced if competing fuels - unconventional oil, synliquids from gas or coal, renewable or nuclear energy - could equal the marginal cost of production. Thus the true cost of oil for the entrance of competitors is less than $10 a barrel. This cost level has already been achieved by some producers of unconventional oil and gas - tar sands in Alberta (Chadwick, 1998), heavy oil in Venezuela (Aalund, 1998), coalbed methane in the United States (BGR, 1998). The question then is, can technological advances balance the higher costs of more difficult production? Experience suggests that the answer is probably yes in the long run. But in the Gulf, marginal costs are unlikely to exceed $5 - $10 a barrel even in the long term.

One question of interest to many upstream investment planners is, when will the call on unconventional fossil occurrences commence? To some extent it is already here. Alberta’s tar sand production started more than 30 years ago and, after some difficulties in the wake of the oil price collapse of 1986, it is now competitive in today’s markets. Venezuela’s heavy oil has also been produced for many years. Still, the share of unconventional oil - and, for that matter, natural gas - is only about 6 percent of world production.

The future production profile of unconventional oil will be a function of the demand for oil products, the price and availability of conventional oil, and the cost and availability of oil substitutes. So what are the prospects for future conventional oil production? The answer is by no means conclusive. The February 1998 issue of the *Explorer,* the journal of the American Association of Petroleum Geologists, writes that "it is not comforting that

experts disagree on almost every aspect of the world outlook, from annual production to current reserves to projected energy demand...One majority opinion emerges: Sometime in the coming century, world-wide production of petroleum liquids will reach a peak and then begin to decline...[but] there is little agreement about when this will happen, and how steep or gradual the decline will be".

TABLE 5.6. ESTIMATED COAL RESOURCES (BILLIONS OF TONNES OF COAL EQUIVALENT)

Region	**Hard coal**	**Soft coal/ lignite**	**Total (exajoules)**
North America	674	201	25,638
Latin America and Caribbean	37	2	1,143
Western Europe	337	11	10,196
Central and Eastern Europe	106	14	3,516
Former Soviet Union	3,025	751	110,637
Middle East and North Africa	1	1	58
Sub-Saharan Africa	181	< 1	5,303
Pacific Asia	7	5	352
South Asia	84	1	2,491
Centrally planned Asia	429	35	13,595
Pacific OECD	139	67	6,030
Total	**5,021**	**1,089**	**178,959**

Note: Includes reserves.

Source: BGR, 1998.

TABLE 5.7. AGGREGATE FOSSIL ENERGY OCCURRENCES

Type	**Consumption**				**Reserves**		**Resourc**	
	1860 - 1998		**1998**					
	Exajoules	**Gigatonnes of carbon**	**Exajoules**	**Gigatonnes of carbon**	**Exajoules**	**Gigatonnes of carbon**	**Exajoules**	**Gi of**
Oil								
Conventional	4,854	97	132.7	2.65	6,004	120	6,071	
Unconventional	285	6	9.2	0.18	5,108	102	15,240	
Natural gas[c]								
Conventional	2,346	36	80.2	1.23	5,454	83	11,113	
Unconventional	33	1	4.2	0.06	9,424	144	23,814	
Coal	5,990	155	92.2	2.40	20,666	533	179,000	
Total	**13,508**	**294**	**319.3**	**6.53**	**46,655**	**983**	**235,238**	

a. Reserves to be discovered or resources to be developed as reserves. b. The sum of reserves and resources. c. Includes natural gas liquids.

Source: Compiled by author from tables 5.1 - 5.6.

Assuming ultimately recoverable conventional oil resources of, say, 400 gigatonnes and a demand development of about 1.5 percent a year, conventional oil production will peak around 2030 (reach the depletion mid-point) with an annual production of 4.4 gigatonnes, up from 3.5 gigatonnes in 1998. Total oil demand, however, would run at 5.8 gigatonnes - implying that unconventional oil will account for 1.4 gigatonnes (Odell, 1998). In other

words, unconventional sources will have to be tapped speedily during the first decade of the 21st century. But experience with unconventional oil production shows a long gestation period and high threshold costs of up to $30 a barrel. Most oil price projections for 2010 (which have an extremely poor track record) expect oil prices of $13 - $29 a barrel.

Thus accelerated expansion of unconventional oil production (primarily tar sands in Alberta and extra heavy oil in Venezuela and Russia) hinges on:

- **Short-term developments in oil prices.**
- **Actual developments in demand.**
- **Technological progress in field growth for conventional occurrences.**
- **Technological advances in the production of unconventional occurrences.**
- **The risk attitude of investors in unconventional production capacity.**

TABLE 5.8. REASONABLY ASSURED URANIUM RESOURCES RECOVERABLE AT LESS THAN $80 A KILOGRAM (RESERVES) AND AT $80 - 130 A KILOGRAM (TONNES OF URANIUM)

Region	< $80 a kilogram[a]	$80 - 130 a kilogram	Total
North America	420,000	251,000	671,000
Latin America and Caribbean	136,400	5,600	142,000
Western Europe	37,300	53,500	90,800
Central and Eastern Europe	14,000	25,800	39,800
Former Soviet Union	564,300	210,200	774,500
Middle East and North Africa	21,000	8,400	29,400
Sub-Saharan Africa	453,600	96,000	549,600
Pacific Asia	0	16,800	16,800

South Asia	5,000	52,000	57,000
Centrally planned Asia	49,300	65,300	114,600
Pacific OECD	615,000	99,600	714,600
Total	**2,315,900**	**884,200**	**3,200,100**

a. Adjusted for mining and milling losses and production of 1997.

Source: NEA and IAEA, 1997.

Sometime in the coming century, world-wide production of petroleum liquids will reach a peak and then begin to decline.

Current market prospects for unconventional oil production remain modest at best. But this may change drastically - for example, changing geopolitics could raise oil prices high enough to facilitate investments in unconventional oil. In general, most oil market outlooks project a steady increase in OPEC's share in global oil production.

Reserves and resources of fissile materials

Naturally occurring fissile materials - natural uranium and thorium - can be found in various types of geological deposits. Although they may occur jointly, most uranium and thorium reside in separate deposits. Like fossil occurrences, uranium and thorium are finite in the Earth's crust, and recoverable quantities depend on demand and market conditions, type of deposit, and technology.

During the 1970s, when large increases in uranium demand before the turn of the century

were expected, the recovery of low-concentration uranium from seawater was investigated. Although technically feasible, estimated production costs appeared prohibitively high relative to alternatives. More recent research and development indicate that the costs of recovering uranium from seawater have fallen considerably, but are still too high given current and expected market prices for uranium. With the declining demand for uranium, recovery is concentrated on terrestrial deposits where uranium availability is estimated according to different production cost categories - such as recoverable at less than $40 a kilogram, less than $80 a kilogram, and less than $130 a kilogram.

Due to the limited development of thorium-fuelled reactors, little effort has been made to explore and delineate thorium. But reserves and resources are known to exist in substantial quantities.

The resource outlook presented below is based on a ‘once-through fuel cycle’ of uranium in normal power reactors - that is, ‘burner’ reactors. But the supply of raw material for reactor fuel is determined not only by uranium presently mined but also by fissile material initially produced for military purposes, which since the mid-1990s has become available for civil use. Reprocessed uranium and plutonium are additional supply sources with the capacity to displace up to 30 percent of the initial demand through recycling.

Uranium reserves

Uranium reserves are periodically estimated by the Organisation for Economic Co-operation and Development’s Nuclear Energy Agency (NEA) together with the International Atomic Energy Agency (IAEA), Uranium Institute (UI), World Energy Council (WEC), and numerous national geological institutions. Although these organisations use different reserve and resource definitions, the differences between their estimates are usually insignificant.

Because NEA-IAEA estimates have the widest coverage, the reserves reported in their

latest survey are reported here (NEA-IAEA, 1997). The two organisations define as reserves those deposits that could be produced competitively in an expanding market. This category is called reasonably assured resources and includes uranium occurrences that are recoverable at less than $80 a kilogram. (Because of declining market prospects, a number of countries have begun to report estimates of reasonably assured uranium resources at less than $40 a kilogram.[6]) Uranium reserves are estimated at 2.3 million tonnes (table 5.8). These reserves are sufficient to meet the demand of existing and planned nuclear power plants well into the 21st century.

The fission of 1 kilogram of natural uranium produces about 573 gigajoules of thermal energy - some 14,000 times as much as in 1 kilogram of oil. But this is still only a small fraction of the energy potentially available from the uranium; up to 100 times this amount can be derived in a fast neutron reactor (a technology that is well developed but not commercially viable). In today's plants, 22 tonnes of uranium are typically needed to produce 1 terawatt-hour of electricity.

Uranium resources

Uranium resources are classified according to the degree of their geological assurance and the economic feasibility of their recovery. Resources that cost less than $80 a kilogram to recover (that is, reasonably assured resources) are considered reserves. Under higher market price assumptions, reasonably assured resources recoverable at less than $130 a kilogram would also qualify as reserves. Resources beyond these categories have been estimated, but with a lower degree of geological assurance. NEA-IAEA (1997) define two categories of estimated additional resources, EAR-I and EAR-II.[7] Another resource category, speculative resources, is also applied. While reasonably assured resources and EAR-I include known or delineated resources, EAR-II and speculative resources have yet to be discovered (table 5.9). Global conventional uranium reserves and resources total about 20 million tonnes.

In addition, vast quantities of unconventional uranium resources exist, essentially low-concentration occurrences that were of temporary interest when medium-term demand expectations for uranium were thought to exceed known conventional resources. Such unconventional resources include phosphate deposits with uranium concentrations of 100 - 200 parts per million in sedimentary rocks, and in exceptional conditions more than 1,000 parts per million in igneous rocks. The uranium content of the world's sedimentary phosphates is estimated at nearly 15 million tonnes, more than half of them in Morocco. To date the only way to extract uranium on an industrial basis, demonstrated mainly in the United States, is through recovery from phosphoric acid. This liquid-liquid separation process uses solvent to extract uranium, allowing for the recovery of up to 70 percent of the uranium contained in the ore. Globally, phosphoric acid plants have a theoretical capacity of supplying about 10,000 tonnes of uranium a year, provided economic conditions can be met.

TABLE 5.9. ESTIMATED ADDITIONAL AMOUNTS AND SPECULATIVE RESOURCES OF URANIUM (TONNES OF URANIUM)

Region	**Estimated additional amount**[a]	**Speculative resources**
North America	2,559,000	2,040,000
Latin America and Caribbean	277,300	920,000
Western Europe	66,900	158,000
Central and Eastern Europe	90,900	198,000
Former Soviet Union	914,000	1,833,000
Middle East and North Africa	12,000	40,000
Sub-Saharan Africa	852,800	1,138,000
Pacific Asia	5,000	0
South Asia	46,000	17,000

Centrally planned Asia	96,500	3,183,000
Pacific OECD	180,000	2,600,00
Total	**5,100,400**	**12,127,000**

a. Includes reasonably assured resources at extraction costs of $130 - 260 a kilogram as well as estimated additional resource categories I and II at less than $260 a kilogram.

Source: NEA and IAEA, 1997.

Other unconventional uranium resources that have been explored are black shale deposits and granite rocks with elevated uranium concentrations. Although their estimated theoretical resource potential is substantial, exploration and extraction have been limited to experimental scales. The low uranium content and potential environmental challenges associated with the production of these occurrences have led to the termination of all efforts. Another low-concentration source of uranium is the vast amount contained in seawater - about 4.5 billion tonnes at 3 parts per billion, often seen as an eventual ‘back-stop’ uranium resource (box 5.3).

BOX 5.3 URANIUM FROM SEAWATER

Seawater contains a low concentration of uranium - less than 3 parts per billion. But the quantity of contained uranium is vast - some 4.5 billion tonnes, or 700 times known terrestrial resources recoverable at less than $130 a kilogram. It might be possible to extract uranium from seawater at low cost. Early research in Japan suggested that it might be feasible to recover uranium from seawater at a cost of $300 a kilogram of uranium (Nobukawa and others, 1994). More recent work in France and Japan suggests that costs might be as low as $80 - 100 a kilogram (Charpak and Garwin, 1998; Garwin, 1999). But these estimates are based on methods used to recover gram quantities of uranium, and unforeseen difficulties may arise in scaling up these methods a million-fold or more. The implications of developing this uranium recovery technology are discussed in chapter 8.

Thorium reserves and resources

Thorium-fuelled burner and breeder reactors were developed in the 1960s and 1970s but fell behind thereafter due to lower than expected market penetration of nuclear power and to a focus on advancing uranium-fuelled nuclear power technologies. Moreover, thorium is not readily useable in a nuclear reactor because the number of neutrons released in each fission makes it difficult to sustain the chain reaction. India has far more thorium than uranium resources, and is attempting to develop the thorium fuel cycle. Important commercial developments of reactors using thorium have not materialised elsewhere. But high-temperature, gas-cooled reactors, like the one in South Africa, could also use a thorium-based fuel cycle. Thorium resources are widely available and could support a large-scale thorium fuel cycle. But given the global availability of inexpensive uranium, thorium-fuelled reactors are unlikely to be significant in resource terms in the next 50 years.

Monazite, a rare-earth and thorium phosphate mineral, is the primary source of thorium. In the absence of demand for rare-earth elements, monazite would probably not be recovered for its thorium content. Other ore minerals with higher thorium contents, such as thorite, would be more likely sources if demand increased significantly. But no thorium demand is expected. In addition, world-wide demand for thorium-bearing rare-earth ores remains low. Thorium disposal is the primary concern in obtaining mining permits for thorium-containing ores. Reserves exist primarily in recent and ancient placer deposits. Lesser quantities of thorium-bearing monazite reserves occur in vein deposits and carbonatites.

TABLE 5.10. ESTIMATED THORIUM RESERVES AND ADDITIONAL RESOURCES (TONNES OF THORIUM)

Region	Reserves	Additional resources
North America	258,000	402,000
Latin America and Caribbean	608,000	702,000
Western Europe	600,000	724,000
Central and Eastern Europe	n.a.	n.a.
Former Soviet Union	n.a.	n.a.
Middle East and North Africa	15,000	310,000
Sub-Saharan Africa	38,000	146,000
Pacific Asia	24,000	26,000
South Asia	319,000	4,000
Centrally planned Asia	n.a.	n.a.
Pacific OECD	300,000	40,000
Total	**2,162,000**	**2,354,000**

n.a. Not available.

Source: BGR Data Bank.

Hydro energy is not evenly accessible, and sizeable hydro resources are often remotely located.

Thorium resources occur in provinces similar to those of reserves. The largest share is contained in placer deposits. Resources of more than 500,000 tonnes are contained in placer, vein, and carbonatite deposits.

Global thorium reserves and resources outside the former Soviet Union and China are estimated at 4.5 million tonnes, of which about 2.2 million tonnes are reserves (table 5.10). Large thorium deposits are found in Australia, Brazil, Canada, Greenland, India, the Middle East and North Africa, South Africa, and the United States. Disseminated deposits in other alkaline igneous rocks contain additional resources of more than 2 million tonnes.

Hydroelectric resources

Hydroelectricity, which depends on the natural evaporation of water by solar energy, is by far the largest renewable resource used for electricity generation. In 1997 hydroelectricity generation totalled 2,566 terawatt-hours (IEA, 1999). Water evaporation per unit of surface area is larger for oceans than for land and, assisted by wind, is the principal cause of the continuous transfer of water vapour from oceans to land through precipitation. The maintenance of a global water balance requires that the water precipitated on land eventually returns to the oceans as runoff through rivers.

As with all renewable resources, the amount of water runoff is finite for a defined amount of time but, all else being equal, this finite amount is forever available. By applying knowledge of the hydrological cycle, the world-wide amount of runoff water can be assessed quite accurately. Hydroelectricity is obtained by mechanical conversion of the potential energy of water. An assessment of its energy potential requires detailed information on the locational and geographical factors of runoff water (available head, flow volumeper unit of time, and so on).

Because rainfall varies by region and even country, hydro energy is not evenly accessible. Moreover, sizeable hydro resources are often remotely located. As a result of advances in

transmission technology and significant capital spending, electricity is being delivered to places far from the generation stations, making energy from water more affordable to more people. Projects considering the connection of electric grids between countries, regions, and even continents have been implemented or are planned (Moreira and Poole, 1993).

Although hydroelectricity is generally considered a clean energy source, it is not totally devoid of greenhouse gas emissions, ecosystem burdens, or adverse socioeconomic impacts (see chapter 3). For comparable electricity outputs, greenhouse gas emissions associated with hydropower are one or two orders of magnitude lower than those from fossil-generated electricity. Ecosystem impacts usually occur downstream and range from changes in fish biodiversity and in the sediment load of the river to coastal erosion and pollution (McCulley, 1996). Potentially adverse socio-economic aspects of hydroelectricity include its capital intensity and social and environmental impacts (McCulley, 1996). Capital-intensive projects with long construction and amortisation periods become less attractive in privatising markets. Higher education levels and increasing population densities along river beds substantially raise the socioeconomic costs of relocation. Local environmental issues require more thorough management than before because modern communications and determined citizen groups can easily turn a remote or local problem into a global issue that can influence international capital and financing markets. Large hydropower projects increasingly encounter public resistance and, as a result, face higher costs.

Integration aspects may increase the competitiveness of hydroelectricity because of its quick response to fluctuations in demand. When hydropower provides spinning reserve and peak supply, this ability allows thermal electric plants to operate closer to their optimal efficiency, lowering fuel costs and reducing emissions from burning fossil fuels. Pump storage might absorb off-peak power or power from intermittent supplies for peak use at a later point.

Theoretical potential

The world’s annual water balance is shown in table 5.11. Of the 577,000 cubic kilometres of water evaporating from ocean and land surfaces, 119,000 cubic kilometres precipitate on land. About two-thirds is absorbed in about equal parts by vegetation and soil; the remaining third becomes runoff water. Most of the fraction absorbed by vegetation and soil evaporates again and amounts to 72,000 cubic kilometres. The difference of 47,000 cubic kilometres is, in principle, available for energy purposes.

The amount of inland precipitation varies slightly by continent, from 740 - 800 millimetres a year. The two exceptions are South America (1,600 millimetres a year) and Antarctica (165 millimetres). Thus runoff water per unit of land area in South America is at least two times that elsewhere.

Convolution of runoff water volumes with average altitudes allows for the evaluation of theoretical hydropower potential by region (table 5.12). Asia (including Pacific Asia, South Asia, and centrally planned Asia) has the largest potential, because its average altitude of 950 metres is the highest of all continents (except Antarctica, which has an average altitude of 2,040 metres). But average altitudes are insufficient for calculating theoretical hydropower potential - runoff is not evenly distributed across a continent. In addition, seasonal variations in runoff influence theoretical potentials. Estimates of the global theoretical hydroelectricity potential range from 36,000 - 44,000 terawatt-hours a year (Raabe, 1985; Boiteux, 1989; Bloss and others, 1980; *World Atlas and Industry Guide,* 1998).

The global water balance and regional precipitation patterns may change as a result of climate change. Current models suggest that global precipitation will increase but that regional precipitation patterns will shift. These changes will affect global hydropower potential.

Technical potential

Appraisals of technical potential are based on simplified engineering criteria with few, if any, environmental considerations. Although the technical potential should exclude economic aspects, these appear to be inherent in such appraisals. Evaluation criteria may differ substantially by country and, especially in developing countries, may be quite unsophisticated. Reported technical potentials could be inflated or, because of incomplete assessments, seriously underestimated (Bloss and others, 1980; *International Water Power and Dam Construction,* 1989; *World Atlas and Industry Guide,* 1998).

TABLE 5.11. ANNUAL WORLD WATER BALANCE

Region	Surface area 10^6 km^2	Precipitation		Evaporation		Runoff[a]	
		Millimetres	Thousands of cubic kilometres	Millimetres	Thousands of cubic kilometres	Millimetres	Thousands of cubic kilometres
Europe	10.5	790	8.3	507	5.3	283	3.0
Asia	43.5	740	32.2	416	18.1	324	14.1
Africa	30.1	740	22.3	587	17.7	153	4.6
North America	24.2	756	18.3	418	10.1	339	8.2
South America	17.8	1,600	28.4	910	16.2	685	12.2
Australia and Oceania	8.9	791	7.1	511	4.6	280	2.5

Antarctica	14.0	165	2.3	0	0.0	165	2.3
Total/average)	149	800	119	485	72	315	47.0
Pacific Ocean	178.7	1,460	260.0	1,510	269.7	-83	-14.8
Atlantic Ocean	91.7	1,010	92.7	1,360	124.4	-226	-20.8
Indian Ocean	76.2	1,320	100.4	1,420	108.0	-81	-6.1
Arctic Ocean	14.7	361	5.3	220	8.2	-355	-5.2
Total/average	361	1,270	458	1,400	505	-130	-47.0
Globe	**510**	**1,130**	**577**	**1,130**	**577**	**0**	**0**

a. Outflow of water from continents into oceans.

Source: UNESC, 1997.

Most significant are the differences in theoretical, technical, and economic potential by region, especially for Africa, North America, and the former Soviet Union (figure 5.3).[8] In general, total technical potential has not been fully measured for most developing countries. In Brazil, for example, hydroelectricity is responsible for 96 percent of electricity generation. Of the 260 gigawatts of technical hydropower potential, more than one-third is accounted as estimated. Of that, 32 gigawatts have never been individually analysed (ANEEL, 1999).

Technological advances tend to increase the technical potential and so broaden the prospects for hydropower meeting future electricity requirements. Improvements in the efficiency and utility of turbines for low-head and small hydro sites permit more effective use of a larger number of sites in a less environmentally intrusive manner. Advances in adjustable-speed generation and new large turbines enable the rehabilitation and expansion of existing capacities (Churchill, 1997). Refurbishment of plants has shown that

advanced technologies can significantly increase the energy output at essentially unchanged primary water flows (*International Water Power and Dam Construction,* 1989; Taylor, 1989). In addition, technological improvements enable the use of previously uneconomical potentials and new sites.

Large hydropower projects increasingly encounter public resistance and, as a result, face higher costs.

But hydroelectric generation is a mature technology for which most components are nearing their practically achievable maximum. As a result further improvements in performance are expected to be modest. Average efficiencies of existing plants are about 85 percent; a 10 percentage point increase would be a major accomplishment.

Economic potential

The economic potential of hydropower is based on detailed economic, social, environmental, geological, and technical evaluations.[9] It is by far the most difficult potential to establish because the financial, environmental, and social parameters that determine it are driven by societal preferences that are inherently difficult to project.

One approach is to use the historically observed fraction of the technical potential used in industrialised countries with extensive hydropower developments. Western Europe has developed 65 percent of its technical hydropower potential, and the United States has developed 76 percent (*World Atlas and Industry Guide,* 1998). A utilisation rate of 40 - 60 percent of a region’s technical potential is a reasonable assumption and leads to a global economic hydroelectricity potential of 6,000 - 9,000 terawatt-hours a year. More detailed

analysis based on current technological and economic puts the global economic potential at 8,100 terawatt-hours a year (see table 5.12).

TABLE 5.12. THEORETICAL, TECHNICAL, AND ECONOMIC HYDROELECTRIC POTENTIALS, INSTALLED CAPACITIES, AND CAPACITIES UNDER CONSTRUCTION, 1997 (TERAWATT-HOURS UNLESS OTHERWISE INDICATED)

Region	Gross theoretical potential	Technical potential	Economic potential	Installed hydro capacity (gigawatts)	Hydropower production	Hydro capacity under construction (megawatts)
North America	5,817	1,509	912	141	697	882
Latin America and Caribbean	7,533	2,868	1,199	114	519	18,331
Western Europe	3,294	1,822	809	16	48	2,464
Central and Eastern Europe	195	216	128	9	27	7,749
Former Soviet Union	3,258	1,235	770	147	498	6,707
Middle East and North Africa	304	171	128	21	66	1,211
Sub-	3,583	1,992	1,288	66	225	16,613

Sub-Saharan Africa	3,583	1,992	1,288	66	225	16,615
Pacific Asia[a]	5,520	814	142	14	41	4,688
South Asia[a]	3,635	948	103	28	105	13,003
Centrally planned Asia	6,511	2,159	1,302	64	226	51,672
Pacific OECD	1,134	211	184	34	129	841
Total	**40,784**	**13,945**	**6,964**	**655**	**2,582**	**124,161**
Total[b]	**40,500**	**14,320**	**8,100**	**660**	**2,600**	**126,000**

a. Several countries in Pacific Asia and South Asia do not publicise their economic potential. As a result the reported economic potentials for the regions are too low - and in South Asia the economic potential is even lower than the electricity generated. b. These are the values listed in the source. They differ from the total in the previous row due to typographical errors and due to the inclusion of estimations for countries for which data are not available.

Source: World Atlas and Industry Guide, 1998.

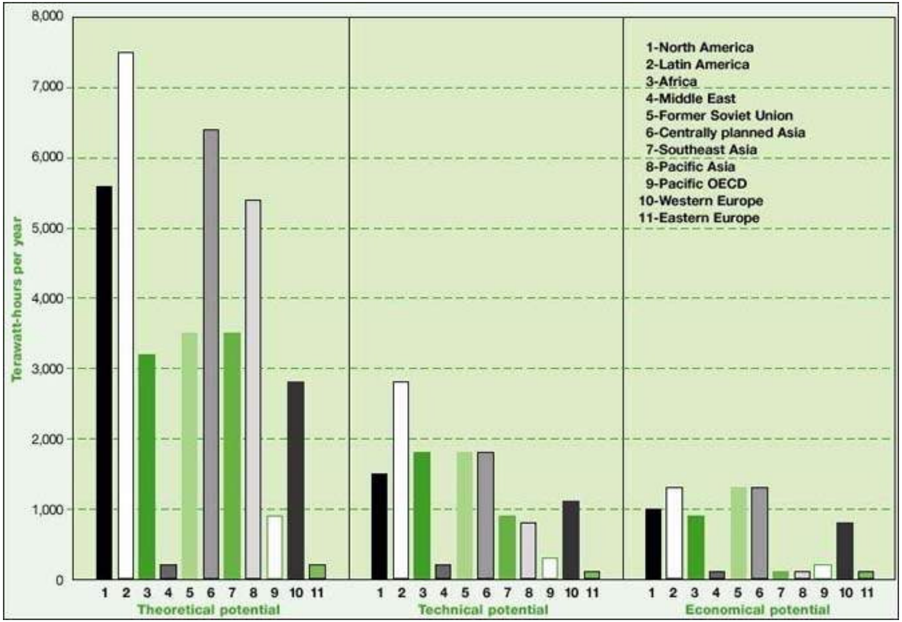


FIGURE 5.3 GLOBAL THEORETICAL, TECHNICAL, AND ECONOMIC HYDROELECTRIC POTENTIALS (TERAWATT-HOURS A YEAR)

Source: World Atlas and Industry Guide, 1998.

Major constraints to hydroelectricity expansion

Physical constraints. Global water runoff is 47,000 cubic kilometres a year, 28,000 cubic kilometres of which is surface runoff and 13,000 of which is stable underground flow into rivers (L’vovich, 1987). Only about three-quarters of the stable underground flow (9,000 cubic kilometres) is easily accessible and economically usable (WRI, 1998). In addition,

3,000 cubic kilometres of useful capacity is available in form of human-made lakes and reservoirs (L'vovich, 1987). Global anthropogenic water withdrawals are about 27 percent of total availability, or 3,250 cubic kilometres a year. Agriculture accounts for 65 percent of the diverted water, industries for 24 percent, and households and other municipal users for 7 percent, while 4 percent is evaporated from reservoirs (Shiklomanov, 1993).

Water use in agriculture totals 2,300 cubic kilometres a year and is expected to increase with growing food demand. The United Nations projects a 50 - 100 percent increase in irrigation water by 2025 (Raskin and others, 1997). Most of the projected increase in water demand will occur in developing countries because of rapid growth in population, industry, and agriculture. Water pollution adds enormously to local and regional water scarcity by eliminating large volumes from the available supply. Many developing countries undergoing rapid industrialisation face the full range of modern toxic pollution problems - eutrophication, heavy metals, acidification, and persistent organic pollutants (WHO, 1997).

Globally, water supplies are abundant. But they are unevenly distributed among and within countries. In some areas water withdrawal has reached such dimensions that surface water supplies are shrinking and groundwater reserves are being depleted faster than they can be replenished by precipitation (WHO, 1997). One-third of the world's people live in countries experiencing moderate to high water stress, and that share could rise to two-thirds by 2025 (WRI, 1998). Since 1940 the amount of freshwater used by humans has roughly quadrupled as the world population has doubled (Population Action International, 1997). Another doubling of the world population by 2100 cannot be ruled out. Assuming an upper limit of usable renewable freshwater of 9,000 - 14,000 cubic kilometres a year, a second quadrupling of world water use appears highly improbable.

In connection with the physical constraints to the use of water for power generation listed above, it should be noted that electricity generation - unlike, say, irrigation and domestic

and industrial uses - is a non-consumptive use of water. Under otherwise favourable conditions, such as irrigation at low altitudes, water can be used first to generate power and then for other purposes.

A physical factor needed to develop hydropower economically is the availability of a suitable head. This limitation does not apply to other water uses. This factor is critical in many water-rich but low-lying regions.

Environmental and social constraints. More than 400,000 cubic kilometres of land have been inundated by the construction of dams (Shiklomanov, 1993). These dams generate 2,600 terawatt-hours a year of electricity. Assuming that all flooded areas are used for hydroelectricity, the energy density is 62 megawatt-hours a hectare per year. But hydroelectric plants vary widely in this respect. Goodland (1996) reports on installed capacity, flooded land, and relocated persons for 34 hydroelectric plants, mostly in developing countries. These plants have an average energy density of 135 megawatt-hours a hectare per year. The most land-intensive of them yields 3.5 megawatt-hours a year per hectare of flooded land, but the least land-intensive yields 1.48 million megawatt-hours a year per hectare.

Eleven of the thirty-four plants yield more than 1,800 megawatt-hours a hectare per year (0.205 kilowatt-years per year), the standard for a fixed array photovoltaic plant in sunny areas (see below). Biomass from forests (15 oven dry tonnes a hectare per year) and from crop plantation (10,000 litres of ethanol a hectare per year using sugarcane) have energy densities of about 20 megawatt-hours a hectare per year. Thus hydroelectricity is land-intensive - more so than photovoltaics but less so than biomass plantations.

Hydroelectricity has sparked controversy when large dams with energy densities as low as 0.2 megawatt-hours a hectare per year require large-scale flooding and displace people. Some large dams involve the resettlement of more than 100,000 people (Goodland, 1997).

Mandatory resettlement and the boom and bust effects of dam construction on local economies have become contentious social and environmental issues. In the past, resettlement was the responsibility of governments and public utilities involved in the project. Despite enormous financial expenditures and compensation packages, resettlement efforts have had modest success. If private utilities are to finance hydro projects, they will have to take responsibility for dealing with resettlement issues.

Biomass-derived fuels can substitute for fossil fuels in existing energy supply infrastructure without contributing to the build-up of greenhouse gases.

National and international cooperation on the development of environmental best practices (such as through working groups on hydropower and the environment in partnership with nongovernmental organisations) may foster public acceptance of hydropower projects. For example, the World Commission on Dams, an independent international commission established in 1998, is reviewing the development effectiveness of large dams and developing internationally acceptable criteria for future decision-making on dams.

Biomass resources

The world derives about 11 percent of its energy from biomass (IEA, 1998b). In developing countries biomass is the most important energy source, accounting for about 35 percent of the total (WEC, 1994). (In the largest developing countries, China and India, biomass accounts for 19 percent and 42 percent of the primary energy supply mix.) But in the world's poorest countries, biomass accounts for up to 90 percent of the energy supply, mostly in traditional or noncommercial forms.[10] This explains why biomass is often

perceived as a fuel of the past - one that will be left behind as countries industrialise and their technological base develops.

But biomass resources are abundant in most parts of the world, and various commercially available conversion technologies could transform current traditional and low-tech uses of biomass to modern energy. If dedicated energy crops and advanced conversion technologies are introduced extensively (see chapter 7), biomass could make a substantial contribution to the global energy mix by 2100. Although most biomass is used in traditional ways (as fuel for households and small industries) and not necessarily in a sustainable manner, modern industrial-scale biomass applications have increasingly become commercially available. In 1996 estimates of biomass consumption ranged from 33 - 55 exajoules (WEC, 1998; IEA, 1998a; Hall, 1997).

Sources

Biomass can be classified as plant biomass (woody, non-woody, processed waste, or processed fuel; table 5.13) or animal biomass. Most woody biomass is supplied by forestry plantations, natural forests, and natural woodlands. Non-woody biomass and processed waste are products or by-products of agroindustrial activities. Animal manure can be used as cooking fuel or as feedstock for biogas generation. Municipal solid waste is also considered a biomass resource.

The annual global primary production of biomatter totals 220 billion oven dry tonnes, or 4,500 exajoules. The theoretically harvestable bioenergy potential is estimated to be 2,900 exajoules, of which 270 exajoules could be considered technically available on a sustainable basis (Hall and Rosillo-Calle, 1998). Hall and Rao (1994) conclude that the biomass challenge is not availability but sustainable management, conversion, and delivery to the market in the form of modern and affordable energy services. Biomass resources can be converted to chemical fuels or electricity through several routes (see

chapter 7).

Two major studies have recently acknowledged the benefits of sustainably produced biomass energy in future energy scenarios. The first is by Shell International Petroleum Company (Shell, 1996), which assessed potential major new sources of energy after 2020, when renewable energies are expected to become competitive with fossil fuels. The Intergovernmental Panel on Climate Change (IPCC, 1996a) has considered a range of options for mitigating climate change, and increased use of biomass for energy features in all its scenarios.

The expected role of biomass in the future energy supply of industrialised countries is based on two main considerations:

- **The development of competitive biomass production, collection, and conversion systems to create biomass-derived fuels that can substitute for fossil fuels in existing energy supply infrastructure without contributing to the build-up of greenhouse gases in the atmosphere. Intermittent renewables, such as wind and solar energy, are more challenging to fit into existing distribution and consumption schemes.**

- **The potential resource base is generally considered substantial given the existence of land not needed or unsuitable for food production, as well as agricultural food yields that continue to rise faster than population growth.**

In developing countries an assessment of potential bioenergy development must first address issues ranging from land-use conflicts with food production to health and environmental problems.

Perceptions and problems

Biomass is often perceived as a fuel of the past because of its low efficiency, high pollution, and associations with poverty.

- **Biomass is the fuel most closely associated with energy-related health problems in developing countries. Exposure to particulates from biomass or coal burning causes respiratory infections in children, and carbon monoxide is implicated in problems in pregnancy (see chapter 3).**

- **Biomass fuels are bulky and may have a high water content. Fuel quality may be unpredictable, and physical handling of the material can be challenging. But technologies for biomass fuel upgrading (into pellets or briquettes, for example) are advancing, and the development of dedicated energy crops will also improve fuel standardisation.**

- **For biomass to become a major fuel, energy crops and plantations will have to become a significant land-use category. Land requirements will depend on energy crop yields, water availability, and the efficiency of biomass conversion to usable fuels. Assuming a 45 percent conversion efficiency to electricity and yields of 15 ovendry tonnes a hectare per year, 2 square kilometres of plantation would be needed per megawatt of electricity of installed capacity running 4,000 hours a year.**

- **The energy balance is not always favourable. While woody biomass energy output is 10 - 30 times greater than the energy input, the issue is less clear for liquid fuels derived from biomass (Shapouri, Duffield, and Graboski, 1995). Nevertheless, the use of sugarcane as a source of ethanol yields a very positive balance and is responsible for a net abatement of 9 million tonnes of carbon a year in Brazil (Moreira and Goldemberg, 1999). With the promising development of enzymatic hydrolysis, cellulose can be transformed into ethanol with a very favourable energy balance (PCAST, 1997).**

- **Large-scale production of biomass can have considerable negative impacts on soil fertility, water and agrochemical use, leaching of nutrients, and biodiversity and landscape. The collection and transport of biomass will increase vehicle and infrastructure use and air-borne emissions.**

Technical potential of biomass energy plantations

To estimate future technical biomass potentials, it is necessary to know:

- **The amount of land available for biomass plantation.**
- **The regional distribution of this land and distances to consumption centres.**
- **The productivity of the land for biomass production, including water availability.**
- **The environmental implications of biomass production.**
- **The technical and economic performance of conversion technologies and net energy balance.**

TABLE 5.13. TYPES AND EXAMPLES OF PLANT BIOMASS

Woody biomass	Non-woody biomass	Processed waste	Processed fuels
• Trees • Shrubs and scrub • Bushes such as coffee and tea • Sweepings from forest floor • Bamboo • Palms	• Energy crops such as sugarcane • Cereal straw • Cotton, cassava, tobacco stems and roots (partly woody) • Grass • Bananas, plantains, and the like • Soft stems such as pulses	• Cereal husks and cobs • Bagasse • Wastes from pineapple and other fruits • Nut shells, flesh, and the like • Plant oil cake	• Charcoal (wood and residues) • Briquette/densified biomass • Methanol/ethanol (wood alcohol) • Plant oils from palm, rape, sunflower, and the like

	and potatoes • Swamp and water plants	• Sawmill wastes • Industrial wood bark and logging wastes • Black liquor from pulp mills • Municipal waste	• Producer gas • Biogas

Source: Adapted from IEA, 1998a.

TABLE 5.14. CURRENT GLOBAL LAND-USE PATTERN

Cropland (arableland and permanent crops)		**Forests and woodland**		**Permanent pastures**		**Other land**		
						Total other land		**Land with rainfed cultivation potential**
Gha	**% of total**	**Gha**	**% of total**	**Gha**	**% of total**	**Gha**	**% of total**	**Gha**
1.5	11	4.2	21	3.4	26	4.0	31	1.6 - 1.8

Note: Gha stands for billions of hectares. Total land availability is 13.1 billion hectares.

Source: FAO, 1993, 1999; Fischer and Heilig, 1998; WRI, 1998.

TABLE 5.15. PROJECTED BIOMASS ENERGY POTENTIAL, 2050 (BILLIONS OF HECTARES UNLESS OTHERWISE INDICATED)

1	**2**	**3**	**4**	**5**	**6a**	**7b**	**7c**

Region	Population in 2050 (billions)	Land with crop production potential in 1990	Cultivated land in 1990	Additional cultivated land required in 2050	Maximum additional area for biomass production	Maximum additional amount of energy from biomass (exajoules)	
Industrialised countries[d]	-	-	0.670	0.050	0.100	17	30
Latin America							
Central and Caribbean	0.286	0.087	0.037	0.015	0.035	6	11
South America	0.524	0.865	0.153	0.082	0.630	107	189
Africa							
East	0.698	0.251	0.063	0.068	0.120	20	36
Central	0.284	0.383	0.043	0.052	0.288	49	86
North	0.317	0.104	0.040	0.014	0.050	9	15
Southern	0.106	0.044	0.016	0.012	0.016	3	5
West	0.639	0.196	0.090	0.096	0.010	2	3
Asia (excl. China)							
Western	0.387	0.042	0.037	0.010	-0.005	0	0
South-central	2.521	0.200	0.205	0.021	-0.026	0	0
East	1.722	0.175	0.131	0.008	0.036	6	11
South-east	0.812	0.148	0.082	0.038	0.028	5	8

China	-	-	-	-	-	**2[e]**	**2[e]**
Total[f]	**8.296**	**2.495**	**0.897**	**0.416**	**1.28**	**226**	**396**
Global biomass energy potential						**276[g]**	**446[g]**

a. (6) = (3) - (4) - (5). b. (7) = (6) x 8.5 [oven dry tonnes a hectare per year] x 20 [GJ per oven dry tonne] based on higher heating value (18 GJ per oven dry tonne for lower heating value). The assumptions for biomass productivity may appear on the high side, but they represent technically achievable yields given dedicated research, development, and dissemination. c. (7) = (6) ×15 [oven dry tonnes a hectare per year] ×20 [GJ per oven dry tonne] based on higher heating value (18 GJ per oven dry tonne for lower heating value). d. OECD, Central and Eastern Europe, newly independent states of the former Soviet Union. e. Data are projected values from d'Apote (1998), not maximum estimates. f. Totals in (2), (3), (4), and (5) exclude industrialised countries. g. Includes 50 EJ of current biomass energy generation.

Source: Derived from Fischer and Heilig, 1998; d'Apote, 1998; Nakicenovic, Grbler, and McDonald, 1998.

Current land-use patterns are shown in table 5.14. Land use is split into cropland, forests and woodland, permanent pastures, and other land. 'Other land' includes uncultivated land, grassland not used for pasture, built-on areas, wastelands, wetlands, roads, barren land, and protected forests. Less than a half of this land (1.6 - 1.8 billion hectares) can be used for rainfed cultivation, including biomass production (FAO, 1993; Fischer and Heilig, 1998).

Because energy plantations will likely account for 80 - 100 percent of biomass supply,

large-scale use of biomass may compete with land for agriculture and food production. But biomass production for energy purposes should not infringe on food production. By 2100 an additional 1,700 million hectares of land are expected to be needed for agriculture, while 690 - 1,350 million hectares of additional land would be needed to support biomass energy requirements under a high-growth biomass energy scenario. Hence land-use conflicts could arise.

Land availability. Considerable areas are potentially available for large-scale production of biomass. In tropical countries large areas of deforested and degraded lands could benefit from the establishment of bioenergy plantations. While the theoretical potential of biomass production is one order of magnitude larger than current global energy use, the technical and economic potentials are much smaller. Technical and economic potentials will be determined by numerous factors ranging from current uses of degraded land (which in developing countries is often used by the poor to graze livestock) and land productivity to the economic reach of the land with respect to centres of energy demand.

The United Nations Food and Agriculture Organization’s "World Agriculture towards 2010 study (Alexandratos, 1995) assesses potential cropland resources in more than 90 developing countries. In 2025 developing countries will be using only 40 percent of their potential cropland, but with large regional variations. Asia (excluding China, for which data were unavailable) will have a deficit of 47 million hectares, but yields of most food crops are low, and there is great potential for improvement using better genetic strains and management techniques. Modern agricultural technologies have not reached many rural farmers and could boost yields by as much as 50 percent. Whether future productivity gains can avoid a food deficit remains to be seen. Africa currently only uses 20 percent of its potential cropland and would still have 75 percent remaining in 2025. Latin America, currently using only 15 percent of its potential cropland, would have 77 percent left in 2025 - land capable of producing nearly eight times its present energy consumption.

Large areas of surplus agricultural land in North America and Europe could become significant biomass production areas. U.S. farmers are paid not to farm about 10 percent of their land, and in the European Union 15 percent of arable farmland can be set aside (amounting to 15 - 20 million hectares by 2010, and possibly more than 50 million hectares later in the 21st century). In addition to more than 30 million hectares of cropland already set aside in the United States to reduce production or conserve land, another 43 million hectares of cropland have high erosion rates. Another 43 million hectares have wetness problems that could be eased with a shift to perennial energy crops. The U.S. Department of Agriculture estimates that a further 60 million hectares may be idled over the next 25 years.

A projection of these parameters for 2050 is shown in table 5.15. The theoretical and technical potential for biomass energy is about ten times current use (445 exajoules relative to 45 exajoules) and close to current global primary energy use of 402 exajoules a year. But the extent to which this potential can be achieved will depend on numerous factors. These include the share of land allocated to other uses (for example, plantations for timber and pulp), actually achievable specific biomass productivity, technologies for converting biomass to convenient energy services, transport distances, water availability, biodiversity, and the need for fertilisers.

Water resources. The supply of freshwater may become a limiting factor for both food and bioenergy production. Several studies have addressed water issues related to agriculture (FAO, 1999; Fischer and Heilig, 1998; WRI, 1998; Seckler and others, 1998, Falkenmark, 1997). But water availability for biomass production has not been addressed in great detail. The common view is that "the food needs of the world’s rapidly growing population will introduce severe problems, either because the rate of growth will be too rapid for the additional water mobilisation to be met, or because the overall water demands will grow unrealistically high so that they cannot be met" (Falkenmark, 1997, p. 74).

Current and projected water resources, by region, are shown in table 5.16. Two levels of water requirements can be used to estimate water sufficiency. The lowest level of sufficiency is generally considered to be 1,000 cubic metres per capita a year, while the availability of more than 2,000 cubic metres per capita a year makes for a small probability of water shortages (Seckler and others, 1998, Falkenmark, 1997). In addition, a recent study commissioned by the United Nations Commission on Sustainable Development (Raskin and others, 1997) puts the upper limit of sustainable water consumption at 40 percent of available resources.

Even without considering water requirements for biomass production, water shortages (supply below 2,000 cubic metres per capita a year) are possible for about half the world's population as early as 2025. Thus the water constraint for extended biomass production will likely be of importance, especially in the long term (see also the section on physical constraints to hydroelectricity expansion, above).

TABLE 5.16. SUFFICIENCY OF WATER RESOURCES, 1990 AND 2025

Region	Population in 1990 (millions)	Water resources per capita in 1990 (cubic metres)	Water resources per capita in 2025 (cubic metres)	Supply in 2025 as percentage of available water resources
North America	278	19,370	36,200	6,065
Latin America and Caribbean	433	30,920	200	533
Western Europe	459	10,604	47,700	1,178

Central and Eastern Europe	277	1,902	10,700	744
Former Soviet Union	428	4,561	36,700	4,981
Middle East and North Africa	n.a.	n.a.	0	6
Sub-Saharan Africa	n.a.	n.a.	< 100	1,465
Pacific Asia	405	11,463	5,100	10
South Asia	1,133	4,537	2,000	1,611
Centrally planned Asia	1,252	2,987	18,600	2,344
Pacific OECD	144	8,463	41,600	1,729
Total	**4,809**	**8,497**	**198,900**	**20,666**

n.a. Not available.

Source: Seckler and others, 1998.

TABLE 5.17. CURRENT AND FEASIBLE BIOMASS PRODUCTIVITY, ENERGY RATIOS, AND ENERGY YIELDS FOR VARIOUS CROPS AND CONDITIONS

Crop and conditions	Yield (dry tonnes a hectare per year)	Energy ratio	Net energy yield (gigajoules a hectare per year)
Short rotation crops(willow, hybrid poplar; United States, Europe)			
• Short term	10-12	10:1	180-200
• Longer term	12-15	20:1	220-260
Tropical plantations(such as eucalyptus)			
• No genetic improvement, fertiliser use, and irrigation	2-10	10:1	30-180
• Genetic improvement and fertiliser use	6-30	20:1	100-550
• Genetic improvement, fertiliser and water added	20-30		340-550
Miscanthus/switchgrass			
• Short term	10-12	12:1	180-200
• Longer term	12-15	20:1	220-260
Sugarcane (Brazil, Zambia)	15-20	18:1[a]	400-500
Wood (commercial forestry)	1- 4	20/30:1	30- 80
Sugar beet(northwest Europe)			
• Short term	10-16	10:1	30-100

• Longer term	16-21	20:1	140-200
Rapeseed (including straw yields; northwest Europe)			
• Short term	4- 7	4:1	50- 90
• Longer term	7-10	10:1	100-170

a. The value in Moreira and Goldemberg (1999) - 7.9:1 - includes spending on transportation and processing of sugarcane to the final product ethanol.

Source: Biewinga and. van der Bijl, 1996; Hall and Scrase, 1998; IEA, 1994; Kaltschmitt, Reinhardt, and Stelzer, 1996; de Jager, Faaij, and Troelstra, 1998; IPCC, 1996a; Ravindranath and Hall, 1996.

Energy balances and biomass productivity

The energy production per hectare of various crops depends on climatic, soil, and management conditions. Examples of net energy yields - output minus energy inputs for agricultural operations, fertiliser, harvest, and the like - are given in table 5.17. Generally, perennial crops (woody biomass such as willow, eucalyptus, hybrid poplar, miscanthus or switchgrass grasses, sugarcane) perform better than annual crops (which are planted and harvested each year; examples include sorghum and hemp). This is because perennial crops have lower inputs and thus lower production costs as well as lower ecological impacts. Different management situations - irrigation, fertiliser application, genetic plant improvements, or some combination of the three - can also increase biomass productivity, by a factor of up to 10.

In addition to production and harvesting, biomass requires transportation to a conversion facility. The energy used to transport biomass over land averages about 0.5 megajoules per tonne-kilometre, depending on infrastructure and vehicle type (Borjesson, 1996). This

means that land transport of biomass can become a significant energy penalty for distances of more than 100 kilometres. But such a radius covers a surface of hundreds of thousands of hectares, and is sufficient to supply enough biomass for conversion facilities of hundreds of megawatts of thermal power.

Transporting biomass by sea is also an option. Sea transport from Latin America to Europe, for example, would require less than 10 percent of the energy input of the biomass (Agterberg and Faaij, 1998). International transport of biomass (or rather, energy forms derived from biomass) is feasible from an energy (and cost) point of view. Sea transport of biomass is already practised: large paper and pulp complexes import wood from all over the world.

Agricultural and forestry residues and municipal waste

Agricultural and forestry residues are the organic by-products from food, fibre, and forest-product industries. Hall and others (1993) estimate the energy contents of these residues at more than one-third of global commercial energy use, of which about 30 percent is recoverable. Limitations arise from the impracticality of recovering all residues and from the need to leave some residues at the site (for fertilisation, for example) to ensure sustainable production of the main product.

Forestry residues obtained from sound forest management do not deplete the resource base. Under sustainable management, trees are replanted, the forest is managed for regeneration to enhance its health and future productivity, or both steps are taken. Energy is just one of the many outputs of forests. One of the difficulties is accurately estimating the potential of residues that can be available for energy use on a national or regional scale.

Municipal solid waste and industrial residues are indirect parts of the biomass resource base. Industrialised countries generate 0.9 - 1.9 kilograms per capita of municipal solid

waste every day. Energy contents range from 4 - 13 megajoules per kilogram (IPPC, 1996a). Johansson and others (1993) report heating values as high as 15.9 megajoules per kilogram in Canada and the United States. Waste incineration, thermochemical gasification, and biodigestion convert municipal solid waste into electricity, heat, or even gaseous and liquid fuels. Because landfill disposal of municipal solid waste in densely populated areas is increasingly constrained and associated with rising tipping fees, such energy conversion can be profitable. Separating and recycling non-combustible contents.

Municipal solid waste incineration requires tight air pollution abatement due to the generation of complex compounds, some of which - such as dioxins - are carcinogenic (WEC, 1994). Advanced pollution abatement equipment essentially eliminates harmful pollutant emissions (Chen, 1995).

Johansson and others (1993) project that in industrialised countries energy production from urban refuse will reach about 3 exajoules a year by 2025.[11] Data on municipal solid waste in developing countries could not be found, but with rising living standards these same as those in low-income OECD countries. Globally, this could double the potential energy supply from municipal solid waste to 6 exajoules.

Environmental implications of biomass production

Forest energy plantations consist of intensively managed crops of predominantly coppiced hardwoods, grown on cutting cycles of three to five years and harvested solely for use as a source of energy. The site, local, regional, and global impacts of these crops need to be considered. For example, if short-rotation energy crops replace natural forests, the main negative effects include increased risks of erosion, sediment loading, soil compaction, soil organic matter depletion, and reduced long-term site productivity. Water pollution from intensively managed sites usually results from sediment loading, enhanced nutrient concentrations, and chemical residues from herbicides. In contrast, if short-rotation crops

replace unused or degraded agricultural land, this reduces erosion, nutrient leaching, and so on.

Developing new crops is a slow and costly process involving many technical and non-technical obstacles (Rosillo-Calle and others, 1996). Farmers have been slow to adopt new crops because of the long-term (more than 15 years) commitment needed. But research and development in Sweden and the United Kingdom have found frost- and pest-resistant clones and generated high yields by using mixed-clone planting and other management practices (Hall and Scrase, 1998).

Soil and nutrients. The abundant use of fertilisers and manure in agriculture has led to considerable environmental problems in various regions. These problems include nitrification of groundwater, saturation of soils with phosphate (leading to eutrophication), and difficulties meeting drinking water standards. In addition, the application of phosphates has increased heavy metal flux to the soil.

The agricultural use of pesticides can affect the health of people as well as the quality of groundwater and surface water - and, consequently, plants and animals. Specific effects depend on the type of chemical, the quantities used, and the method of application. Experience with perennial crops (willow, poplar, eucalyptus) suggests that they meet strict environmental standards. Agrochemical applications per hectare are 5 - 20 times lower for perennial energy crops than for food crops like cereals (Hall, 1997).

Limited evidence on the soil effects of energy forestry indicates that our understanding of this area is still relatively poor. Current evidence indicates that, with proper practices, forest soil management need not negatively affect physical, chemical, and biological soil parameters. Soil organic matter can improve soil fertility, biology, and physical properties (such as bulk density and water relations).[12] Relative to arable agriculture, energy plantations can improve the physical properties of soil because heavy machinery is used

less often and soil disturbances are fewer. Soil solution nitrate can also be significantly reduced in soils planted with fast-growing trees, as long as nitrogen fertilisers are applied in accordance with the nutrient demands of the trees.

In tropical countries large areas of deforested and degraded lands could benefit from the establishment of bioenergy plantations.

Biological fertilisers may replace chemical nitrogen fertilisers in energy forestry and crops.

Biological fertilisation may include:

- **Direct planting of nitrogen-fixing woody species and interplanting with nitrogen-fixing trees or ley crops.**
- **Soil amendments with various forms of organic matter (sewage sludge, wastewater, contaminated groundwater, farmyard manure, green manure).**
- **Stimulation or introduction of rhizosphere micro-organisms that improve plant nutrient uptake.**
- **Biological fallow.**

Overall, from a nutritional point of view, there is no reason to believe that energy forest plantations will have significant environmental and ecological impacts when proper management practices are applied (Ericson, 1994).

Erosion. Erosion is related to the cultivation of many annual crops in many regions and is

a concern with woody energy crops during their establishment phase. Little field data are available for comparison with arable crops. One of the most crucial erosion issues relates to the additional soil stabilisation measures required during the establishment of energy plantations. Growing ground-cover vegetation strips between rows of trees can mitigate erosion as long as competition does not occur.

Changing land use from agricultural production to an energy forest plantation reduces precipitation excess (groundwater recharges) and nutrient leaching. Nitrogen leaching decreases with energy plantations because the standard nutrient supply and the use of animal slurries lead to good uptake efficiencies relative to agricultural production systems. Nitrogen uptake efficiency for arable crops is about 50 percent, for grass 60 percent, and for forest plantations about 75 percent. The losses in these systems are mainly due to leaching and de-nitrification (Rijtman and Vries, 1994).

Another concern relates to possible soil compaction caused by heavy harvesting machinery. But these effects tend to be small to moderate due to the infrequency of forest harvesting (Smith, 1995). Overall, these impacts can be significantly lower than for conventional agriculture. When harvesting perennials, soil erosion can be kept to an absolute minimum because the roots remain in the soil. In the United States millions of hectares covered by grasses that fall under the soil conservation programme could provide a promising biomass production area, since biomass production can be combined with soil protection. Another benefit of perennial crops relative to annual crops is that their extensive root system adds to the organic matter content of the soil. Generally, diseases (such as eels) are prevented and the soil gets a better structure.

Many of the environmental and ecological impacts noted thus far can be alleviated with compensating measures. Energy crops are generally more environmentally acceptable than intensive agriculture because chemical inputs are lower and the soil undergoes less disturbance and compaction.

Biodiversity and landscape. Biomass plantations may be criticised because the range of biological species they support is much narrower than is found in natural ecosystems, such as forests. While this is generally true, it is not always relevant. Where plantations are established on degraded or excess agricultural lands, the restored lands are likely to support a more diverse ecology than before. Moreover, degraded land areas are plentiful: in developing countries about 0.5 billion hectares of degraded land are available (Bekkering, 1992). In any case, it is desirable to restore such land surfaces for water retention, erosion prevention, and microclimate control.

A good plantation design - including set-aside areas for native plants and animals situated in the landscape in a natural way - can avoid problems normally associated with monocultures. The presence of natural predators (such as insects) can also prevent the outbreak of pests and diseases. Altogether, more research and insights on plantations are needed, taking into account local conditions, species, and cultural aspects.

Environmentally motivated responses to biomass production

Management practices are a key factor in the sustainable production and use of biomass. Yet very little is known about managing large-scale energy forest plantations or even agricultural and forestry residues for energy use.[13] The potential adverse environmental effects of large-scale dedicated energy crops and forestry plantations have raised concerns. Considerable effort has gone into investigatingthese concerns, and much knowledge has been gained (see Tolbert, 1998 and Lowe and Smith, 1997).

As a result good practice guidelines are being developed for the production and use of biomass for energy in Austria, Sweden, the United Kingdom, and the United States, as well as across Europe.

TABLE 5.18 ANNUAL SOLAR ENERGY RECEIVED BY THE EARTH

Parameter	Energy
Solar energy intercepted by the Earth at ~1.37 kilowatts per square metre	5.5×10^6
Solar energy reflected by the atmosphere back to space at ~0.3 kilowatts per square metre)	1.6×10^6
Solar energy potentially usable at ~1.0 kilowatts per square metre	3.9×10^6
Ratio of potentially usable solar energy to current primary energy consumption (402 exajoules)	~9,000

Source: Author's calculations.

Very little is known about managing large-scale energy forest plantations or even agricultural and forestry residues for energy use.

These guidelines focus on short-rotation coppice and recognise the central importance of site-specific factors and the breadth of social and environmental issues that should be taken into consideration. But given that residues may remain more widely used than energy crops for quite some time, guidelines are urgently needed on when it is appropriate to use residues for energy, what fraction can be used, and how potential environmental advantages can be maximised.

A key message of these guidelines is that site and crop selection must be made carefully, and the crop must be managed sensitively. Energy crops should not displace land uses of high agricultural and ecological value. Consideration needs to be given to the landscape and visibility, soil type, water use, vehicle access, nature conservation, pests and

diseases, and public access (ETSU, 1996; Hall and Scrase, 1998). The guidelines also stress the importance of consulting with local people at the early planning stage, and of ongoing community involvement in the development stages. Issues such as changes to the landscape, increased traffic movements, or new employment opportunities in rural areas may prove very significant to local people.

Economics

The production costs of plantation biomass are already favourable in some developing countries. Eucalyptus plantations in Brazil supply wood chips for $1.5 - 2.0 a gigajoule (Carpentieri, Larson, and Woods, 1993). Based on this commercial experience, Carpentieri, Larson, and Woods (1993) project future biomass (wood chip) production of 13 exajoules a year on 50 million hectares of land. Costs are much higher in industrialised countries (with top values of around $4 a gigajoule in parts of Europe). But in the longer run, by about 2020, better crops and production systems are expected to cut biomass production costs in the United States to $1.5 - 2.0 a gigajoule for substantial land surfaces (Graham and others, 1995; Turnure and others, 1995).

Biomass costs are influenced by yield, land rent, and labour costs. Thus increases in productivity are essential to reducing biomass production costs. Yields can be improved through crop development, production integration (multiproduct plantation), and mechanisation. Competition for land use should be avoided to minimise inflated land rental rates. Labour costs can be lowered through mechanisation.

Solar energy resources

Solar energy has immense theoretical potential. The amount of solar radiation intercepted by Earth is more than three orders of magnitude higher than annual global energy use (table 5.18). But for several reasons the actual potential of solar energy is somewhat lower:

- **Time variation. The amount of solar energy available at a given point is subject to daily and seasonal variations. So, while the maximum solar flux at the surface is about 1 kilowatt per square meter, the annual average for a given point can be as low as 0.1 - 0.3 kilowatts per square meter, depending on location. For large-scale application of solar energy - more than 5 - 10 percent of the capacity of an integrated electricity system - the variability of insolation necessitates energy storage or backup systems to achieve a reliable energy supply.**

- **Geographic variation. The availability of solar energy also depends on latitude. Areas near the equator receive more solar radiation than subpolar regions. But geographic variation can be significantly reduced by using collectors capable of following the position of the sun. Polar regions show a notable increase in irradiance due to light reflection from snow.**

- **Weather conditions. Weather is another, even stronger, factor influencing the availability of solar energy. Annual average sky clearness may vary by 80 - 90 percent in locations such as Khartoum (Sudan), Dakar (Bangladesh), Kuwait, Baghdad (Iraq), Salt Lake City (Utah), and by 40 - 50 percent in Tokyo (Japan) and Bonn (Germany; WEC, 1994). Solar irradiance is often quite diffuse, leading to lower average power densities. Thus large-scale generation of solar energy can require significant land.**

- **Siting options. While building structures provide interesting local siting possibilities,[14] large-scale solar collectors can be located on land that is not being used - which amounts to about 4 billion hectares (FAO, 1999). Assuming 10 percent of this unused land is allocated for habitation (cities, towns, villages) and infrastructure (roads, ports, railways), some 3.6 billion hectares are available for solar energy.**

Large-scale availability of solar energy will thus depend on a region's geographic position, typical weather conditions, and land availability. Using rough estimates of these factors, solar energy potential is shown in table 5.19. This assessment is made in terms of primary energy - that is, energy before the conversion to secondary or final energy is estimated. The amount of final energy will depend on the efficiency of the conversion device used (such as the photovoltaic cell applied). Issues related to energy conversion and its impact on the amount of energy delivered are considered in chapter 7.

This assessment also reflects the physical potential of solar energy. Thus it does not take into account possible technological, economic, and social constraints on the penetration of solar energy except for two different assumptions on available land. The consideration of such constraints is likely to result in much lower estimates - as in WEC (1994), where global solar energy potential in 2020 ranges from 5 - 230 exajoules a year.

The solar energy potential in table 5.19 is more than sufficient to meet current and projected energy uses well beyond 2100. Thus the contribution of solar energy to global energy supplies will not be limited by resource availability. Rather, three factors will determine the extent to which solar energy is used in the longer run: the availability of efficient and low-cost technologies to convert solar energy into electricity and eventually hydrogen, of effective energy storage technologies for electricity and hydrogen, and of high-efficiency end-use technologies fuelled by electricity and hydrogen.

TABLE 5.19. ANNUAL SOLAR ENERGY POTENTIAL (EXAJOULES)

Region	Minimum	Maximum
North America	181.1	7,410
Latin America and Caribbean	112.6	3,385
Western Europe	25.1	914

Central and Eastern Europe	4.5	154
Former Soviet Union	199.3	8,655
Middle East and North Africa	412.4	11,060
Sub-Saharan Africa	371.9	9,528
Pacific Asia	41.0	994
South Asia	38.8	1,339
Centrally planned Asia	115.5	4,135
Pacific OECD	72.6	2,263
Total	**1,575.0**	**49,837**
Ratio to current primary energy consumption (402 exajoules)	**3.9**	**124**
Ratio to projected primary energy consumption in 2050 (590 - 1,050 exajoules)	**2.7 - 1.5**	**84 - 47**
Ratio to the projected primary energy consumption in 2100 (880 - 1,900 exajoules)	**1.8 - 0.8**	**57 - 26**

Note: The minimum and maximum reflect different assumptions on annual clear sky irradiance, annual average sky clearance, and available land area.

Source: IEA, 1998c; Nakicenovic, Grbler, and McDonald, 1998.

Wind energy resources

Winds develop when solar radiation reaches the Earth’s highly varied surface unevenly, creating temperature, density, and pressure differences. Tropical regions have a net gain of heat due to solar radiation, while polar regions are subject to a net loss. This means that the Earth’s atmosphere has to circulate to transport heat from the tropics towards the poles. The Earth’s rotation further contributes to semipermanent, planetary-scale

circulation patterns in the atmosphere. Topographical features and local temperature gradients also alter wind energy distribution.

A region’s mean wind speed and its frequency distribution have to be taken into account to calculate the amount of electricity that can be produced by wind turbines. Wind resources can be exploited in areas where wind power density is at least 400 watts per square metre at 30 metres above the ground (or 500 watts per square metre at 50 metres). Moreover, technical advances are expected to open new areas to development. The following assessment includes regions where the average annual wind power density exceeds 250 - 300 watts per square metre at 50 metres - corresponding to class 3 or higher in the widely used U.S. classification of wind resources.

TABLE 5.20. ANNUAL WIND ENERGY POTENTIAL

Region	Percentage of land area	Population density (people per square kilometre)	Gross electric potential (thousands of terawatt-hours)	Assessed wind energy potential (exajoules)	Estimated second-order potential (thousands of terawatt-hours)	Assessed wind energy potential, (exajoules)
Africa	24	20	106	1,272	10.6	127
Australia	17	2	30	360	3	36
North America	35	15	139	1,670	14	168
Latin America	18	15	54	648	5.4	65
Western Europe	42	102	31	377	4.8	58

Eastern Europe and former Soviet Union	29	13	106	1,272	10.6	127
Asia (excl. former Soviet Union)	9	100	32	384	4.9	59
Total	**23**		**500**	**6,000**	**53**	**640**

Note: Refers to wind energy with average annual power density of more than 250 - 300 watts per square metre at 50 metres (resources class 3 and higher in the U.S. classification of wind resources). The energy equivalent in exajoules is calculated based on the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines, including transmission losses), resulting in a primary energy estimate. Totals are rounded.

Source: Grubb and Meyer, 1993.

TABLE 5.21. ESTIMATED ANNUAL WIND ENERGY RESOURCES

Region	**Land surface with wind class 3 - 7**		**Wind energy resources without land restriction**		**Wind energy resources if less than 4 percent of land is used**	
	Percent	**Thousands of**	**Thousands of**	**Exajoules**	**Thousands of**	**Exajoules**

		square kilometres	**terawatt-hours**		**terawatt-hours**	
North America	41	7,876	126	1,512	5.0	60
Latin America and Caribbean	18	3,310	53	636	2.1	25
Western Europe	42	1,968	31	372	1.3	16
Eastern Europe and former Soviet Union	29	6,783	109	1,308	4.3	52
Middle East and North Africa	32	2,566	41	492	1.6	19
Sub-Saharan Africa	30	2,209	35	420	1.4	17
Pacific Asia	20	4,188	67	804	2.7	32
China	11	1,056	17	204	0.7	8
Central and South Asia	6	243	4	48	0.2	2
Total[a]	**27**	**30,200**	**483**	**5,800**	**18.7**	**231**

Note: The energy equivalent in exajoules is calculated based on the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines, including transmission losses), resulting in a primary energy estimate. a. Excludes China.

Source: WEC, 1994.

Several studies have analysed the global potential of power production using wind. To define technical wind power potential, one needs take into account siting constraints. First-order exclusions may include definite constraints such as cities, forests, difficult terrain, and inaccessible mountain areas. The most important limitations arise from social, environmental, and land-use constraints, including visual and noise impacts, all of which depend on political and social judgements and traditions and may vary by region. Regional estimates of wind electricity potentials (class 3 and above) are summarised in table 5.20.

Grubb and Meyer (1993) estimate the theoretical electricity generation potential of global wind energy resources (class 3 and above) to be 500,000 terawatt-hours a year (see table 5.20). Only about 10 percent of this theoretical potential may be realistically harvested.

WEC (1994) places the global theoretical wind potential at 483,000 terawatt-hours a year (table 5.21). This estimate is based on the assumption that 27 percent of the Earth's land surface is exposed to an annual mean wind speed higher than 5.1 metres per second at 10 metres above ground (class 3 and above), and that this entire area could be used for wind farms. WEC also suggests a more conservative estimate of 19,000 terawatt-hours a year, assuming for practical reasons that just 4 percent of the area exposed to this wind speed can be used for wind farms. (The 4 percent estimate comes from detailed studies of wind power potential in the Netherlands and the United States.)

Geothermal energy resources

Geothermal energy is generally defined as heat stored within the Earth. The Earth's temperature increases by about 3 degrees Celsius for every 100 metres in depth, though this value is highly variable. Heat originates from the Earth's molten interior and from the decay of radioactive materials.

Four types of geothermal energy are usually distinguished:

- **Hydrothermal - hot water or steam at moderate depths (100 - 4,500 metres).**
- **Geopressed - hot-water aquifers containing dissolved methane under high pressure at depths of 3 - 6 kilometres.**
- **Hot dry rock - abnormally hot geologic formations with little or no water.**
- **Magma - molten rock at temperatures of 700 - 1,200 degrees Celsius.**

Today only hydrothermal resources are used on a commercial scale for electricity generation (some 44 terawatt-hours of electricity in 1997) and as a direct heat source (38 terawatt-hours of heat; Bjrnsson and others, 1998).

The global potential of geothermal energy is on the order of 140,000,000 exajoules. But a much smaller amount can be classified as resources and reserves (table 5.22). Still, geothermal energy has enormous potential. Even the most accessible part, classified as reserves (about 434 exajoules), exceeds current annual consumption of primary energy. But like other renewable resources (solar energy, wind energy), geothermal energy is widely dispersed. Thus the technological ability to use geothermal energy, not its quantity, will determine its future share. The regional distribution of geothermal energy potential is shown in table 5.23.

Environmental aspects of geothermal energy use relate primarily to gas admixtures to the geothermal fluids such as carbon dioxide, nitrogen, hydrogen sulphides or ammonia and heavy metals such as mercury. The quantities vary considerably with location and temperatures of the feed fluid but are generally low compared to those associated with fossil fuel use. Because the chemicals are dissolved in the feed water which is usually re-injected into the drill holes, releases are minimal.

Ocean energy resources

Four types of ocean energy are known:

- **Tidal energy - energy transferred to oceans from the Earth's rotation through gravity of the sun and moon.**
- **Wave energy - mechanical energy from wind retained by waves.**
- **Ocean thermal energy - energy stored in warm surface waters that can be made available using the temperature difference with water in ocean depths.**
- **Salt gradient energy - the energy coming from salinity differences between freshwater discharges into oceans and ocean water.**

Tidal energy is the most advanced in terms of current use, with a number of commercial plants in operation. Despite notable progress in recent years, the other ocean energy resources are generally not considered mature enough for commercial applications.

TABLE 5.22. ANNUAL GEOTHERMAL POTENTIAL (EXAJOULES)

Resource category	Energy
Accessible resource base (amount of heat that could theoretically be tapped within a depth of 5 kilometres)	140,000,000
Useful accessible resource base	600,000
Resources (portion of the accessible resource base expected to become economical within 40 - 50 years)	5,000
Reserves (portion of the accessible resource base expected to become economical within 10 - 20 years)	500

Source: Palmerini, 1993; Bjrnsson and others, 1998.

TABLE 5.23. ANNUAL GEOTHERMAL POTENTIAL BY REGION (EXAJOULES)

Resource category	Energy
North America	26,000,000•(18.9)
Latin America and Caribbean	26,000,000•(18.6)
Western Europe	7,000,000•(5.0)
Eastern Europe and former Soviet Union	23,000,000•(16.7)
Middle East and North Africa	6,000,000•(4.5)
Sub-Saharan Africa	17,000,000•(11.9)
Pacific Asia (excl. China)	11,000,000•(8.1)
China	11,000,000•(7.8)
Central and South Asia	13,000,000•(9.4)
Total	**140,000,000**

Note: Numbers in parentheses are shares of world total.

Source: WEC, 1994; EPRI, 1978.

TABLE 5.24. ANNUAL OCEAN ENERGY POTENTIAL

Resource category	Terawatt-hours	Exajoules
Tidal energy	22,000	79
Wave energy	18,000	65
[illegible]	2,000,000	7,200

Ocean thermal energy[a]	2,000,000	7,200
Salt gradient energy[b]	23,000	83
Total	**2,063,000**	**7,400**

a. The potential of ocean thermal energy is difficult to assess but is known to be much larger than for the other types of ocean energy. The estimate used here assumes that the potential for ocean thermal energy is two orders of magnitude higher than for tidal, wave, or salt gradient energy. b. Assumes the use of all the world's rivers with devices of perfect efficiency.

Source: WEC, 1994, 1998; Cavanagh, Clarke, and Price, 1993.

The theoretical potential of each type of ocean energy is quite large (table 5.24). But like other renewables, these energy resources are diffuse, which makes it difficult to use the energy. The difficulties are specific to each type of ocean energy, so technical approaches and progress differ as well.

Conclusion

Globally, energy resources are plentiful and are unlikely to constrain sustainable development even beyond the 21st century (tables 5.25 and 5.26). If historical observations are any indication, possible intergenerational equity conflicts on resource availability and costs will most likely be equilibrated by technological progress. The fossil resource base is at least 600 times current fossil fuel use, or 16 times cumulative fossil fuel consumption between 1860 and 1998. (The resource base does not include methane clathrates and other oil, gas, and coal occurrences, the inclusion of which could quadruple the resource base.)

While the availability and costs of fossil fuels are unlikely to impede sustainable

development, current practices for their use and waste disposal are not sustainable (UNCED, 1993). In their natural states, energy resources are environmentally inert (from the perspective of sustainable development). Even mining and production of fossil resources interfere little with sustainable development relative to current pollution emissions and wastes associated with their combustion for the provision of energy services. Thus the economic and environmental performance of fossil, nuclear, and renewable conversion technologies - from resource extraction to waste disposal - will determine the extent to which an energy resource can be considered sustainable.

Relative economic and environmental aspects make up the demand pull for the development of future energy resources. Sociopolitical preferences and policies can appreciably amplify or weaken the demand pull. In many countries, especially transition economies but also several energy-exporting developing countries, the domestic fossil energy resource endowment has yet to be evaluated using market-based criteria. Such evaluations may lead to a substantial revision of readily available reserve volumes and point to unforeseen investments in up-stream operations to raise productivity to international standards.

Energy resources are not evenly distributed across the globe. Although renewables are more evenly distributed and accessible than fossil and nuclear resources, their economic potential is affected by land-use constraints, variation of availability as a function of latitude (solar power) and location (wind power and hydroelectricity), solar irradiation, and water and soil quality (biomass). Still, renewable energy flows are three orders of magnitude larger than current global energy use (figure 5.4). Their use will depend primarily on the commercialisation of conversion technologies. Similarly, uranium and thorium resources are plentiful and do not pose a constraint to the long-term deployment of nuclear power.

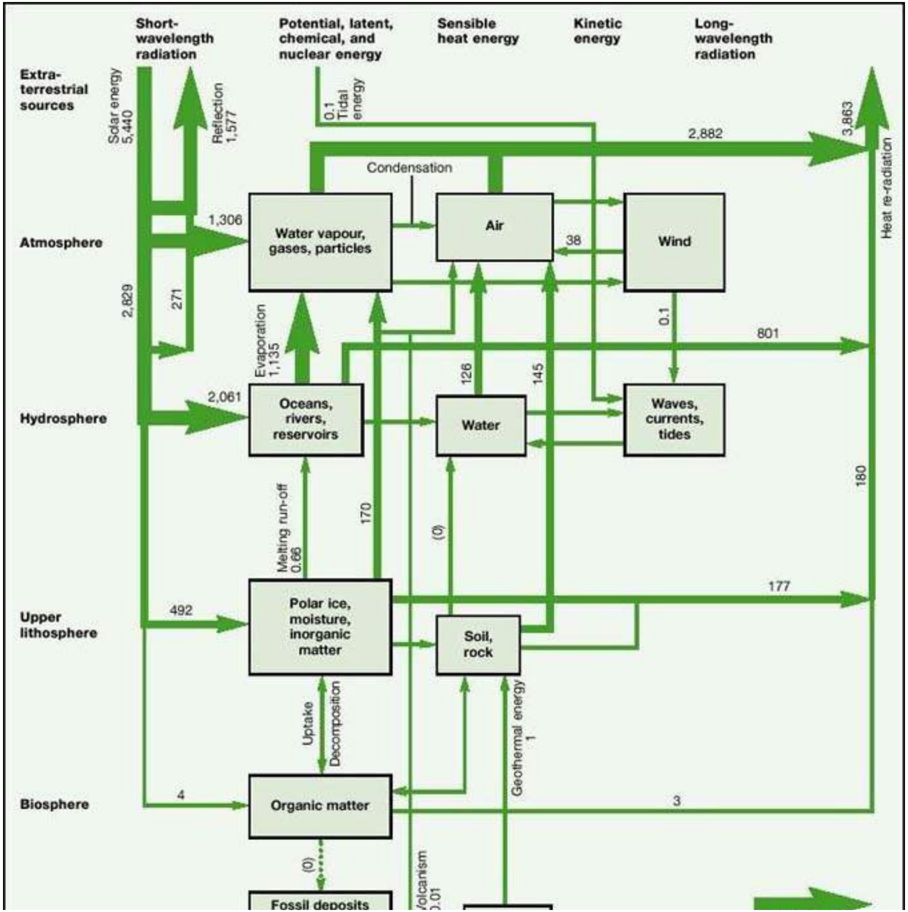
TABLE 5.25. SUMMARY OF GLOBAL FOSSILE AND FISSILE RESOURSES (THOUSANDS OF

EXAJOULES)

Resource	Consumed by end 1998	Consumed in 1998	Reserves	Resources	Resource base[a]	Additional occurrences
Oil	5.14	0.14	11.11	21.31	32.42	45
Conventional	4.85	0.13	6.00	6.07	12.08	
Unconventional	0.29	0.01	5.11	15.24	20.35	45
Gas	2.38	0.08	14.88	34.93	49.81	930
Conventional	2.35	0.08	5.45	11.11	16.57	
Unconventional	0.03	0.00	9.42	23.81	33.24	930
Coal	5.99	0.09	20.67	179.00	199.67	
Fossile total	**13.51**	**0.32**	**46.66**	**235.24**	**281.89**	**975**
Uranium						
Open cycle in thermal reactors[b]	n.e.	0.04	1.89	3.52	5.41	7.1[c]
Closed cycle with fast reactors[d]	-	-	113	211	325	426[b]
Fossile and fissile total[e]	**n.e.**	**0.36**	**48**	**446**	**575**	**1,400**

n.e. Not estimated. - Negligible. a. Sum of reserves and resources. b. Calculated from the amount in tonnes of uranium, assuming 1 tonne = 589 terajoules (IPCC, 1996a). c. Does not include uranium from seawater or other fissile materials. d. Calculated assuming a 60-fold increase relative to the open cycle, with 1 tonne = 35,340 terajoules. e. All totals are rounded.

Source: Author’s calculations from previous chapter tables.



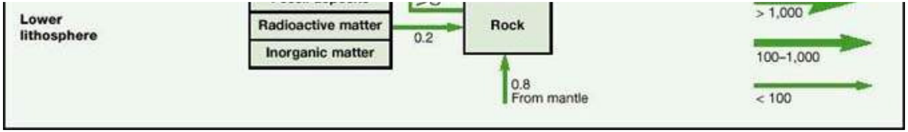


FIGURE 5.4. GLOBAL ENERGY BALANCE AND FLOWS WITHOUT ANTHROPOGENIC INTERFERENCE

Note: Energy flows are in thousands of exajoules a year. Numbers in parentheses are uncertain or rounded.

Source: Srensen, 1979.

Most long-term energy demand and supply scenarios involve increasing global energy trade, irrespective of the underlying assumptions of energy resource and technology development. Supply security considerations may tilt the balance in favour of one energy resource or set of resources. Supply security improves with the share of energy supplies from national sources. A thorough evaluation of a nation’s energy resource endowment based on market criteria is an important step towards supply security.

The world energy system’s current dependence on fossil fuel conversion is considered unsustainable by the United Nations (UNDP, 1997). It has often been assumed that fossil resource limitations or the "running out of resources" phenomenon (Meadows and others, 1972) would wean the energy system off fossil sources and bring about the necessary course correction towards sustainable energy development. Based on long-term global energy demand expectations, current understanding of the world’s fossil resource endowment, and production economics, this is unlikely to happen before the end of the 21st century. Thus a transition to sustainable energy systems that continue to rely predominantly on fossil fuels will depend on the development and commercialisation of fossil technologies that do not close their fuel cycle through the atmosphere.[15]

Alternatively, the transition will likely require determined policies to move away from fossil fuels. Large increases in fossil fuel prices as a result of rapid resource depletion are unlikely to drive the transition.

TABLE 5.26. SUMMARY OF THE RENEWABLE RESOURCE BASE (EXAJOULES A YEAR)

Resource	Current use[a]	Technical potential	Theoretical potential
Hydropower	9	50	147
Biomass energy	50	>276	2,900
Solar energy	0.1	>1,575	3,900,000
Wind energy	0.12	640	6,000
Geothermal energy	0.6	5,000	140,000,000
Ocean energy	n.e.	n.e.	7,400
Total	**56**	**> 7,600**	**> 144,000,000**

n.e. Not estimated. a. The electricity part of current use is converted to primary energy with an average factor of 0.385.

Source: Author's calculations from previous chapter tables.

Renewable energy flows are three orders of magnitude larger than current global energy use.

Transitions motivated by factors other than short-term economics usually invoke extra

costs that have to be borne by contemporary societies for the benefit of future ones. In either case - making the use of fossil fuels sustainable or shifting to non-fossil energy sources - society must first recognise that the current energy system is unsustainable and that adequate policy measures need to be introduced. These measures may stimulate technological advances and development, change consumer preferences, or both. After all, the existence of enormous fossil, nuclear, and renewable resources is irrelevant unless there is a demand for them and unless technologies for their extraction and sustainable conversion to energy services are commercially available. Otherwise, resources remain 'neutral stuff'.

Notes

1. However, Masters and others argue that most major oil-producing countries are reporting as proven reserves what the authors would define as identified reserves (proven plus probable plus possible).

2. Oil production costs and market prices may differ significantly, however. Oil is a highly political commodity with market prices that often have little relation to costs. While economic rationality suggests that the least-cost oil reserves are produced first, this has not been the case, at least since 1973. That gives low-cost and lowest-cost producers quite a bit of leverage in engineering market price instabilities or backing out of high-cost production.

3. The ratio of reserves to production assumes constant demand for a resource as well as constant production over the period suggested by the ratio. In essence, it implies that production will plummet from full output in one year to zero output in another. In reality, production peaks and then declines along a quasi-logistic curve, and supplies will last much longer, though at much lower volumes than suggested by the ratio.

4. Once an investment has been committed for gas export pipelines, it cannot easily be

designated for other uses (whereas an oil tanker may be rerouted instantly by a single radio call). Disputes between trading partners may put the investment at risk and lead to disruptions in supply and off take.

5. Temperature increases as a function of high atmospheric carbon concentrations are highly uncertain. For example, the mean global temperature increase estimated for a doubling of carbon dioxide concentrations ranges from 1.5 - 4.5 Kelvin (IPCC, 1996b).

6. Uranium reserves as defined by the Uranium Institute are proven and probable reserves (labelled Reserve Class I) at production costs of less than $40 a kilogram, less than $60 a kilogram, and less than $80 a kilogram. WEC (1998) uses the term *proven reserves* for the NEA-IAEA category reasonably assure resources.

7. The Uranium Institute uses for the lesser-known category Reserve Class II. WEC (1998) defines its estimated additional amounts recoverable to correspond to NEA-IAEA EAR I.

8. A detailed and consistent compilation for all countries is not available, and country-specific information is often published without verification. *The International Water Power and Dams Construction Yearbook* (1998) and even the *World Atlas and Industry Guide* (1998) present a few inconsistencies. Nevertheless, a cross-check showed a similar world total for these two sources.

9. The consideration of social and environmental aspects suggests that this is the market potential. Because of inconsistencies in the definitions used in different appraisals, here the notion of economic potential is maintained.

10. Non-commercial biomass is difficult to account for accurately or goes unreported. For instance, biomass data for China and India are not included in the WEC statistics.

11. It is assumed that 75 percent of the energy in urban refuse can be recovered and that

the waste generation rate per capita is constant over time. Estimates for Canada and the United States are based on a per capita waste generation rate of 330 kilograms a year and a heating value of 15.9 megajoules per kilogram (and a 50 percent recycling rate). Estimates for other OECD countries are based on a per capita waste generation rate of 300 kilograms a year and a heating value of 12.7 megajoules per kilogram.

12. A review of the literature indicates that over time there are few, if any, long-term losses of soil carbon after forest harvesting and reforestation. But substantial losses of soil carbon are reported for systems involving harvesting followed by intensive burning or mechanical site damage. Holistic, life-cycle approaches are required to estimate the contribution of intensive forest management and bioenergy systems to local and global carbon balances.

13. There are exceptions: a lot is known about eucalyptus for charcoal production and sugarcane for ethanol production in Brazil (which tend to follow traditional agricultural and forestry practices). Similarly, there is extensive knowledge about willows for heat power generation in Sweden, where the cultivation of about 16,000 hectares has also borrowed considerably from traditional forestry and agricultural activities.

14. For example, if the performance and costs of solar collectors integrated with buildings are improved, commercial buildings could become local energy production centres. Such integration would enlarge the space available for solar collection and allow buildings to contribute to their energy use.

15. Decarbonisation of fuels (before use) or greenhouse gas abatement (after fuel production or use) and subsequent carbon dioxide disposal could eventually avoid closing the carbon fuel cycle through the atmosphere (see chapters 8 and 11).

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Chapter 6. Energy End-Use Efficiency

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ABSTRACT

Since the 1970s more efficient energy use in OECD countries has weakened or eliminated the link between economic growth and energy use. At the global level just 37 percent of primary energy is converted to useful energy - meaning that nearly two-thirds is lost. The next 20 years will likely see energy efficiency gains of 25-35 percent in most industrialised countries and more than 40 percent in transition economies. Dematerialization and recycling will further reduce energy intensity. Thus energy efficiency is one of the main technological drivers of sustainable development world-wide.

Energy policy has traditionally underestimated the benefits of end-use efficiency for society, the environment, and employment. Achievable levels of economic efficiency depend on a country’s industrialisation, motorization, electrification, human capital, and policies. But their realisation can be slowed by sector - and technology-specific obstacles - including lack of knowledge, legal and administrative obstacles, and the market power of energy industries. Governments and companies should recognise innovations that can lower these obstacles. The external costs of energy use can be covered by energy taxes, environmental legislation, and greenhouse gas emissions trading. There is also an important role for international harmonisation of regulations for efficiency of traded products. Rapid growth in demand provides especially favourable conditions for innovations in developing countries - enabling these countries to leapfrog stages of development if market reforms are also in place.

The economic potentials of more efficient energy use will continue to grow with new

technologies and with cost reductions resulting from economies of scale and learning effects. Considerations of the second law of thermodynamics at all levels of energy conversion and technological improvements at the level of useful energy suggest further potential for technical efficiency of almost one order of magnitude that may become available during this century. Finally, structural changes in industrialised and transition economies - moving to less energy-intensive production and consumption - will likely contribute to stagnant or lower energy demand per capita in these countries.

Today more than 400,000 petajoules a year of primary energy deliver almost 300,000 petajoules of final energy to customers, resulting in an estimated 150,000 petajoules of useful energy after conversion in end-use devices. Thus 250,000 petajoules are lost, mostly as low- and medium-temperature heat. Globally, then, the energy efficiency of converting primary to useful energy is estimated at 37 percent. Moreover, considering the capacity to work (that is, the exergy) of primary energy relative to the exergy needed by useful energy according to the second law of thermodynamics, the efficiency of today's energy systems in industrialised countries is less than 15 percent. But energy efficiency can be improved - and energy losses avoided - during the often overlooked step between useful energy and energy services (figure 6.1).

One main goal of energy analysis in the context of sustainable development is to explore ways to reduce the amount of energy used to produce a service or a unit of economic output - and, indirectly, to reduce related emissions. Two questions are key: How tight is the link between final energy use and the energy service in a given end use? And what is the potential for technological and organisational changes to weaken that link in the next 10-20 years? Because the technologies used in different regions differ substantially, the potential for economic efficiency varies. Still, more efficient energy use is one of the main options for achieving global sustainable development in the 21st century.

This chapter focuses on end-use energy efficiency - that is, more efficient use of final

energy or useful energy in industry, services, agriculture, households, transportation, and other areas (see figure 6.1). Supply-side energy efficiency (energy extraction, conversion, transportation, and distribution) is treated in chapters 5 and 8. Supply-side efficiency has been the focus of energy investment and research and development since the early 20th century. End-use efficiency has received similar attention only since the mid-1970s, having been proven cheaper in many cases but often more difficult to achieve for reasons discussed below.

Energy efficiency - and indirectly, improved material efficiency - alleviates the conflicting objectives of energy policy. Competitive and low (but full-cost) energy prices support economic development. But they increase the environmental burden of energy use. They also increase net imports of conventional energies and so tend to decrease the diversity of supply. Using less energy for the same service is one way to avoid this conflict. The other way is to increase the use of renewable energies (chapter 7).

Recent trends in energy intensity in countries and regions

A sector's energy use, divided by gross domestic product (GDP), is the starting point for understanding differences in the efficient use of final energy by sector, country, or period. With few exceptions, such analyses have been carried out over long periods only in OECD countries (IEA, 1997a; Morovic and others, 1989; Diekmann and others, 1999). These ratios are instructive for what they say about energy use in different economies at a given point in time. They can also be used to measure changes in energy efficiency and other components of energy use - such as changes in the structure and consumption of a given sector or subsector. Changes in energy efficiency are driven by higher prices, technical improvements, new technologies, cost competition, and energy conservation programmes.

More efficient energy use
is one of the main options for

achieving global sustainable development in the 21st century.

OECD countries

Over the past 30 years every OECD country and region saw a sharp decline in ratios of energy to GDP (figure 6.2; box 6.1).[1] Changes in energy use were distributed unevenly among sectors, however, and only part of the decline was related to increased energy efficiency:

- **Industry experienced the largest reductions in ratios of energy to GDP - between 20 and 50 percent. Energy efficiency (if structural change is excluded by holding constant the mix of output in 1990) increased by more than 1 percent a year through the late 1980s, after which lower fuel prices caused a slowdown in improvements (Diekmann and others, 1999). In Japan, the United States, and West Germany the absolute demand for energy by industry dropped about 10 percent because of changes in the mix of products. In other countries structural changes had little impact on energy use.**

- **Among households, energy requirements per unit of floor area fell modestly, led by space heating. Despite far more extensive indoor heating (with more central heating), in almost all OECD countries energy use was lower in the 1990s than in the early 1970s. (The only notable exception was Japan, where income-driven improvements in heating outweighed savings from added insulation in new buildings and from more efficient heating equipment.) In addition, in most countries the unit consumption of appliances (in kilowatt-hours per year) fell. Increased efficiency outpaced trends towards larger appliances. On the structural side, however, household size continued to shrink, raising per capita energy use. New homes had larger areas per capita and more appliances, continuing an income**

effect dating from the early 1950s.

- **Space heating in the service sector also required less energy - in heat per square metre - in most OECD countries. Electricity use remained closely tied to service sector GDP, but showed little upward trend except where electric heating was important. This outcome may be surprising given the enormous importance of electrification and office automation in the service sector. Over time there is a close relationship between electricity use and floor area.**

- **In passenger transportation, energy use is dominated by cars and in a few countries (such as the United States) by light trucks. In Canada and the United States in the early 1990s fuel use per kilometre by light-duty vehicles was 30 percent below its 1973 level, though by 1995 reductions had ceased (figure 6.3). Reductions ceased relative to person-kilometres because there were only 1.5 people per car in the mid-1990s, compared with more than 2.0 in 1970. Europe saw only small (less than 15 percent) reductions in fuel use per kilometre by cars, almost all of which were offset by a similar drop in load factors. Taxes on gasoline and diesel seem to be the main influence on the average efficiency of the car fleet, with the lowest taxes in the United States (averaging $0.10 a litre) and the highest in France ($0.74 a litre). For air travel, most OECD countries experienced more than a 50 percent drop in fuel use per passenger-kilometre due to improved load factors and increased fuel efficiency. Higher mobility per capita and shifts from trains, buses, and local transport towards cars and air travel, however, counterbalanced the efficiency gains in most countries.**

- **Freight transport experienced rather small changes in energy use per tonne-kilometre. Improvements in fuel efficiency were offset by a shift towards trucking. This shift was driven by higher GDP, less shipping of bulk goods by rail and ship, and more lifting of high-value partially manufactured and final goods by trucks and**

aeroplanes.

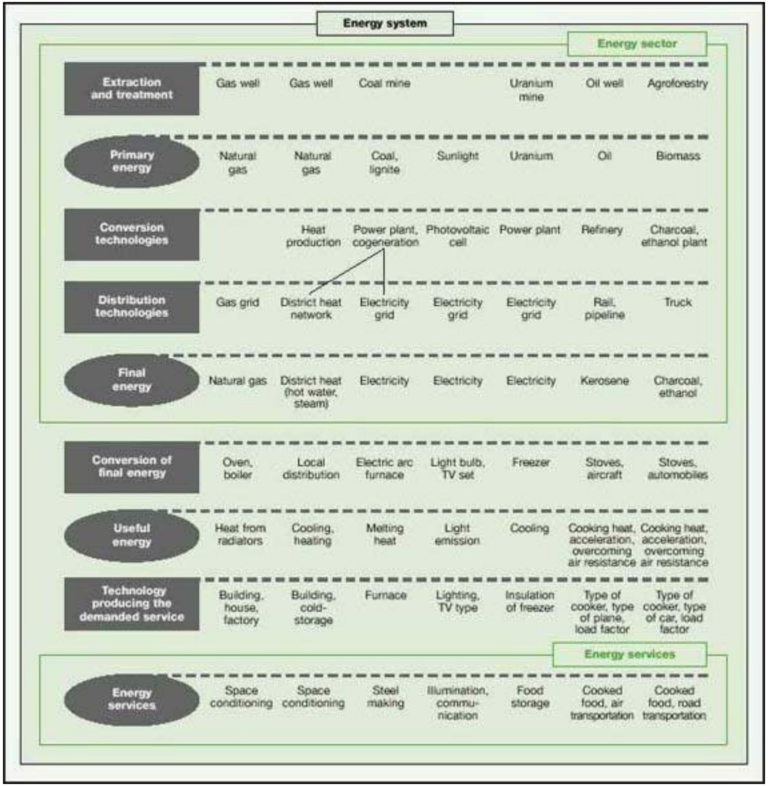


FIGURE 6.1. ENERGY CONVERSION STEPS, TYPES OF ENERGY, AND ENERGY SERVICES: POTENTIALS FOR ENERGY EFFICIENCY

Potential improvements in energy efficiency are often discussed and focused on

> **energy-converting technologies or between the level of final energy and useful energy. But one major potential of energy efficiency, often not strategically considered, is realised at the level of energy services by avoiding energy losses through new technologies. Such technologies include new building materials and window systems, membrane techniques instead of thermal separation, sheet casting instead of steel rolling, biotechnology applications, and vehicles made of lighter materials such as plastics and foamed metals. Energy storage and reuse of break energy, along with better designs and organisational measures, can also increase energy efficiency.**

In most OECD countries energy intensities fell less rapidly in the 1990s than before. One clear reason - besides higher income - was lower energy prices since 1986 and lower electricity prices (due to the liberalisation of the electricity market in many OECD countries), which slowed the rate of energy efficiency improvement for new systems and technologies.

Eastern Europe and the Commonwealth of Independent States

Relative to OECD countries, the statistical basis for ratios of energy to GDP is somewhat limited in Eastern Europe and the Commonwealth of Independent States.[3] Ratios of primary energy demand to GDP have risen in the Commonwealth of Independent States since 1970 (Dobozi, 1991) but began to decline in many Eastern European countries in the mid-1980s (table 6.1). General shortcomings of central planning, an abundance of energy resources in some countries, a large share of heavy industries, low energy prices, and a deceleration of technological progress have been the main reasons for limited progress (Radetzki, 1991; Dobozi, 1991; Sinyak, 1991; Gritsevich, 1993).

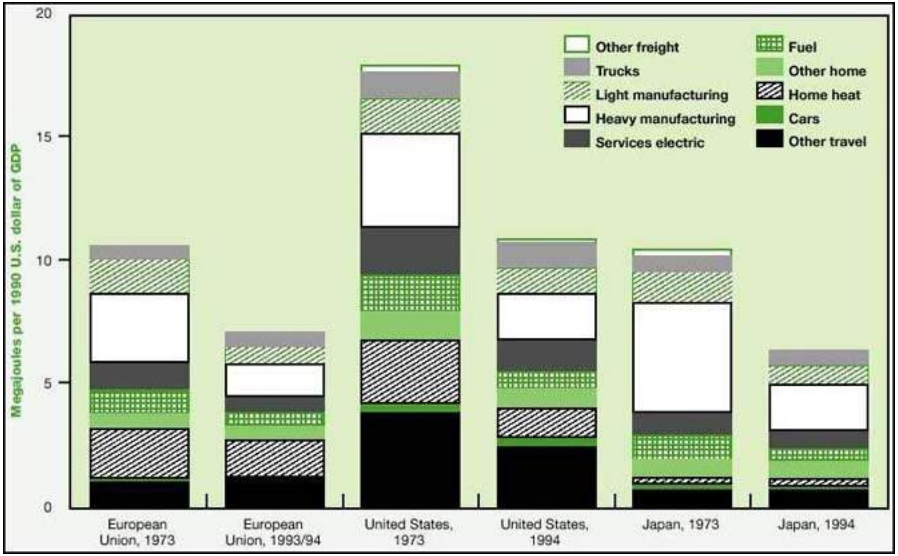


FIGURE 6.2. RATIOS OF ENERGY TO GDP IN OECD COUNTRIES BY END USE, 1973 AND 1994

Note: Measured using purchasing power parity.

Source: Schipper, 1997.

BOX 6.1. DRIVERS OF LOWER ENERGY DEMAND: DEMATERIALIZATION, MATERIAL SUBSTITUTION, SATURATION, AND CHANGING BEHAVIOUR

Like ratios of energy to GDP, the production of energy-intensive materials per unit of GDP is falling in almost all industrialised countries (with a few exceptions such as Australia, Iceland, and Russia). Changes in the production of basic materials may affect changes in ratios of energy to GDP. In many OECD countries declining production of steel and primary aluminium is supporting lower ratios of energy to GDP. But production of young, energy-intensive materials - such as polymers substituting for traditional steel or aluminium use - is increasing relative to GDP. In addition, ratios of energy-intensive materials to GDP are increasing slightly in developing countries, almost balancing out the declines in industrialised countries for steel and primary aluminium over the past 25 years.

Dematerialization has different definitions covering the absolute or relative reduction in the quantity of material used to produce a unit of economic output. In its relative definition of tonnes or volumes of material used per unit of GDP, dematerialization has occurred over several decades in many industrial countries. This shift has contributed to structural changes in industry - particularly in energy-intensive areas such as chemicals and construction materials (Carter, 1996; Jaenicke, 1998; Hinterberger, Luks, and Schmidt-Bleek, 1997).

A number of forces are driving dematerialization in industrialised countries (Ayres, 1996; Bernadini, 1993):

- As incomes rise, consumer preferences shift towards services with lower ratios of material content to price.
- As economies mature, there is less demand for new infrastructure (buildings, bridges, roads, railways, factories), reducing the need for steel, cement, non-ferrous metals, and other basic materials.
- Material use is more efficient - as with thinner car sheets, thinner tin cans, and lighter paper for print media.
- Cheaper, lighter, more durable, and sometimes more desirable materials are substituted - as with the substitution of plastics for metal and glass, and fibre optics for copper.

- Recycling of energy-intensive materials (steel, aluminium, glass, paper, plastics, asphalt) contributes to less energy-intensive production. Recycling may be supported by environmental regulation and taxes (Angerer, 1995).

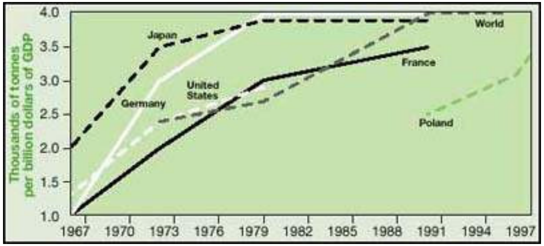
- Reuse of products, longer lifetimes of products (Hiessl, Meyer-Krahmer, and Schn, 1995), and intensified use (leasing, renting, car sharing) decrease new material requirements per unit of service.

- Industrialised countries with high energy imports and energy prices tend to decrease their domestic production of bulk materials, whereas resource-rich developing countries try to integrate the first and second production steps of bulk materials into their domestic industries (Cleveland and Ruth, 1999).

But industrialised countries are also experiencing some of the drivers of increased material use per capita. Increasing urbanisation, mobility, and per capita incomes increase the demand for material-intensive infrastructure, buildings, and products. Smaller households, the increasing importance of suburban communities and shopping centres, and second homes create additional mobility. The move from repair to replacement of products and trends towards throwaway products and packaging work against higher material efficiencies - and, hence, against energy efficiency and sustainable development.

Steel production intensity in various countries, 1961-96

Primary aluminium production intensity in various countries, 1972-96



Polymer production intensity in various countries, 1966-97

Note: For the world, includes all plastics. For France, Germany, Japan, and the United States, includes only polyethylene, polypropylene, polystyrene, and polyvinylchloride.

Source: UN, 1999; German Federal Statistical Office; IEA 1998.

Ratios of primary energy to GDP have gone through two phases in these countries, separated by the onset of economic and political reform in the late 1980s and the 1990s. Whereas the ratio increased in Russia, it declined in Armenia, Belarus, Estonia, Kyrgyzstan, Latvia, and Tajikistan. Among the other members of the Commonwealth of

Independent States the ratio fluctuated for reasons other than improvements in energy efficiency (IEA, 1997a, 1998). Since 1990 the ratio has declined in most Eastern European countries (see table 6.1).

- **In industry, final energy consumption per unit of output fell less than 1 percent a year in Eastern Europe in 1990-97 but increased almost 7 percent a year in Russia (CENEf, 1998).**

- **Transportation saw few changes in energy use per passenger-kilometre or tonne-kilometre for the two main modes, cars and trucks.**

- **Among households, small gains in the thermal integrity of buildings could not overcome increasing demands for heating and comfort. Indeed, in the mid-1980s centrally heated Eastern European buildings required 50-100 percent more final energy per unit of area and per degree day (that is, using standardised winter outdoor temperatures) than similar buildings in Western Europe. Moreover, home appliances were often small and inefficient.**

In the early 1990s economic reforms began to restructure production and consumption patterns and raise once-subsidised energy prices. In the Baltics, the Czech Republic, Hungary, and Poland this phase led to real declines in ratios of primary energy to GDP as efficiency increased and the structure of manufacturing changed (see table 6.1). Several transition economies also saw lower household fuel use for space and water heating. Such changes were often not related to efficiency, however, and were instead caused by energy shortages, higher energy prices, and related changes in heating behaviour.

Overall, transition economies showed a remarkable contraction in energy use by industry, mostly because of structural changes (Bashmakov, 1997a). But this trend has nearly been outweighed by rapid growth in road transportation and (in some countries) in electricity for appliances and services. Structural changes in industry, integration with global

markets, and investments in new processes, buildings, and infrastructure are expected to improve energy efficiency considerably over the next 20 years. These trends will likely help stabilise energy demand despite rising incomes and GDP in these countries.

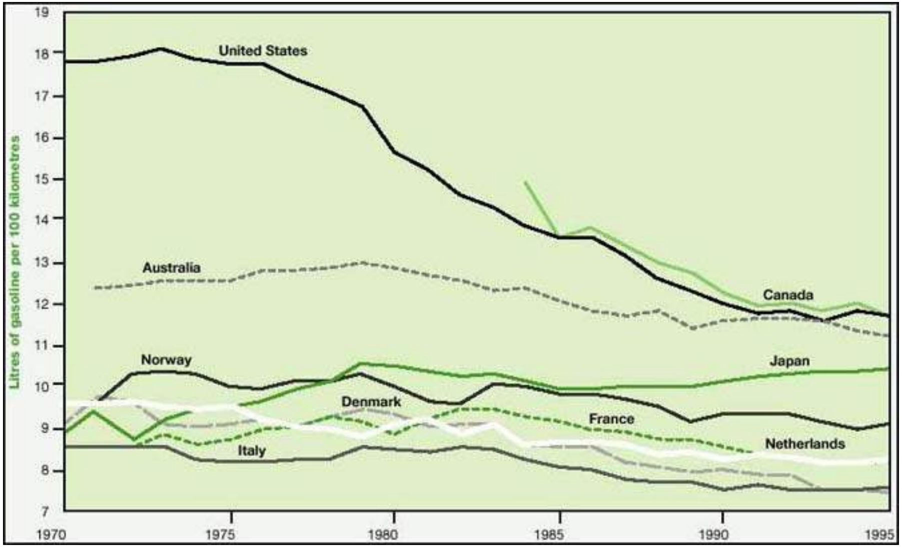


FIGURE 6.3. WEIGHTED AVERAGE OF ON-ROAD AUTOMOBILE GASOLINE AND DIESEL FUEL INTENSITIES IN OECD COUNTRIES, 1970-95

Source: Schipper, 1997.

Developing Asia, Africa, and Latin America

In many developing countries energy use will be driven by industrialisation, urbanisation, increasing road transportation, and increasing personal incomes.[4] Indeed, per capita

energy use in developing countries tends to be higher where per capita incomes are higher (in purchasing power parity terms), as in Latin America, India, and Southeast Asia. Wide income disparities in many developing countries are also reflected in energy consumption patterns. Often a small portion of the population accounts for most commercial energy demand. Data limitations hamper careful analysis in many developing countries, however.

Higher-income developing countries (per capita income above $1,200 in 1998 purchasing power parity terms). Energy demand in industry has fallen in most higher-income developing countries, both as a result of higher energy prices in the 1970s and 1980s and open borders to international competition. China has shown the most dramatic developments, but most Latin American and other Asian economies have also shown energy intensity improvements in this sector. In recent years many manufacturers in industrialised nations have moved energy-intensive industries to developing countries, often to take advantage of cheaper labour, less stringent environmental regulation, and lower overhead and transportation costs. Many of these countries (Brazil, China, India, Indonesia) also need their own basic product industries.

TABLE 6.1. RATIOS OF PRIMARY ENERGY TO GDP IN TRANSITION ECONOMIES, 1985-96

Region/country	Energy consumption per capita, 1996 (gigajoules)	Megajoules per unit of GDP (1990 purchasing power parity dollars)		
		1985	1990	1995
Commonwealth of Independent States	**135**	**29.8**	**29.4**	**41.4**
Belarus	100			20.5
Russia	170			36.8
Ukraine	127			45.2

Eastern Europe	**89[a]**	**23.9**	**21.8**	**20.9**
Bulgaria	120	36.0	29.7	31.8
Czech Republic	165	23.6	19.6	18.2
Hungary	108	18.3	16.5	16.3
Poland	117	26.5	21.6	19.2
Romania	84	28.5	31.8	25.1
Slovenia[b]	124		12.6	13.8
Former Yugoslavia	53[a]	12.6	14.7	21.4

a. Data are for 1995. b. Based on exchange rates.

Source: IEA, 1997a, Kos, 1999.

TABLE 6.2. RATIOS OF PRIMARY ENERGY TO GDP IN DEVELOPING COUNTRIES, 1975-95

Country or region	**Energy consumption per capita, 1996 (gigajoules)**	**Megajoules per unit of GDP (1990 purchasing power parity dollars)**				
		1975	**1980**	**1985**	**1990**	**1995**
China	36.3[a]	23.4	22.6	17.3	15.0	10.9
India	14.6[a]	7.5	7.8	8.3	8.7	9.2
Indonesia	18.4	3.3	4.2	4.6	5.4	5.4
Argentina	64.1	8.0	8.4	9.2	9.6	9.6
Brazil	61.0[a,b]	4.6	4.6	5.0	5.4	5.9
Mexico	61.4	7.2	8.2	8.5	8.7	8.7

Venezuela	94.0[a]	10.5	11.3	12.6	12.1	12.1
North Africa[c]	29.2	5.4	6.3	7.9	8.8	9.4
Southern Africa[d]	27.4	10.8	11.6	15.2	13.9	14.4
Rest of Africa	2.5	2.6	2.9	2.6	2.6	2.9
Middle East	80.4	8.4	10.9	17.6	20.9	22.6

a. Data are for 1996. b. Includes non-commercial energy. c. Ratios of energy to GDP are for Algeria, Egypt, Libya, Morocco, and Tunisia. d. Ratios of energy to GDP are for Nigeria, South Africa, Zambia, and Zimbabwe.

Source: EC, various years; IEA, 1998.

Household appliances, cookers, and water heaters have become more energy efficient in higher-income developing countries. But the rapid acquisition of household devices has far outpaced the impact of greater efficiency.

A similar trend has occurred in the service and public sectors. Buildings in warm higher-income developing countries have increasing rates of air conditioning. Higher lighting levels, increased office automation, and other developments have also contributed to rapidly rising electricity use in this sector (IEA, 1997b).

Transportation accounts for a rising share of energy use in higher-income developing countries. Growing numbers of vehicles, often rising at 1.5 times the rate of GDP growth, have dominated the transportation energy use picture. Many cars and light trucks sold in

the developing world have become less fuel intensive. But increased urbanisation and traffic congestion and reduced occupancy have eaten up many of the improvements in vehicle technology.

Overall, more efficient manufacturing does not dominate the increase in ratios of primary energy to GDP in higher-income developing countries (Argentina, Brazil, India, Mexico). Increasing numbers of cars and trucks, electrification of rural areas, and increased energy use by households have played a bigger role (table 6.2). Such energy uses were hardly mature before the 1970s. Motor vehicles and household appliances were far more expensive, in real terms, than they are today. Today such items are less costly and, more important, are often made in developing countries. (China is an exception to this pattern. In 1978, when it initiated economic reform, China exploited economies of scale in manufacturing - such as steel-making - to realise high efficiency improvements in industry and energy.)

Lower-income developing countries (per capita income below $1,200 in 1998 purchasing power parity terms). The situation in lower-income developing countries is somewhat different.

- **When disposable income increases, energy consumption by households in low-income developing countries shifts from traditional to commercial fuels. This trend has significant implications for energy efficiency in households. Since the technical efficiencies of cooking appliances using commercial fuels are higher than those of biomass, composite energy consumption per household tends to fall. A typical example is the move from a fuelwood stove with a technical efficiency of 12-18 percent to a kerosene stove with an efficiency of 48 percent, or to a liquefied petroleum gas stove with an efficiency of 60 percent. On the other hand, the substitution of commercial for traditional fuels raises ratios of energy to GDP, because traditional energy is typically not included when such ratios are calculated.**

In addition, electrification in rural areas and increasing income and mobility in urbanising areas increase energy use.

- **Most of the technology used by industry in lower-income developing countries is imported from industrialised countries. Thus these industries should continue to benefit from technological improvements that promote rational energy use (see below). While this is expected to make energy demand fall, the use of obsolete and energy-inefficient technology imported from industrialised countries will drive the specific energy demand of industry.**

- **Similarly, the transportation sector should benefit from the global trend towards improving vehicle fuel efficiency. Because lower-income developing countries import vehicles from other countries, the energy intensity of road transport should decrease. But the large share of used vehicles imported by lower-income developing countries is helping to maintain a relatively old car stock with high specific fuel demand.**

In many developing countries energy use will be driven by industrialisation, urbanisation, increasing road transportation, and increasing personal incomes.

Energy intensity in lower-income developing countries will largely depend on the interplay between these factors. Although available data (which are patchy at best) show that, for example, Africa’s ratio of energy to GDP increased by 1.8 percent a year in 1975-95, that trend may be substantially influenced by the substitution of commercial for non-commercial forms of energy.

Potential benefits of technology transfer

In many cases used factories, machines, and vehicles from industrialised countries are transferred to developing or transition economies, saddling them with inefficient equipment and vehicles for many years.[5] The transfer of energy-efficient equipment and vehicles to developing and transition economies offers an important opportunity for leapfrogging the typical development curves of energy intensity and for achieving sustainable development while maximising know-how transfer and employment opportunities. The transfer of energy-efficient technology represents a win-win-situation for the technology provider and the recipient. Benefits on the receiving end include reduced energy imports, increased demand for skilled workers, job creation, reduced operating costs of facilities, and faster progress in improving energy efficiency. The scope for improving energy efficiency through technology transfer can be seen by comparing energy uses in various industries and countries (table 6.3).

TABLE 6.3. FINAL ENERGY USE IN SELECTED INDUSTRIES AND COUNTRIES, MID-1990S (GIGAJOULES PER TONNE)

Country	Steel	Cement	Pulp and paper
India	39.7	8.4	46.6
China	27.5-35.0	5.9	
United States	25.4	4.0	40.6
Sweden	21.0	5.9	31.6
Japan	17.5	5.0	

Source: Lead authors.

Used equipment and vehicles are traded for lack of capital, lack of life-cycle costing by investors, the investor-user dilemma (see below), and lack of public transportation in developing countries (President’s Committee of Advisors on Science and Technology, 1999, p. 4-3; IPCC, 1999b). Thus high efficiency standards for products, machinery, and vechicles in OECD countries will also affect standards in developing and transition economies, particularly for mass-produced and tradable products and for world-wide investments by global players. Opportunities for technology transfer among developing countries will also become more important and should be encouraged. Many of these countries already have well-established domestic expertise and produce goods, technologies, and services suitable for the conditions and climates of other developing countries.

Transition economies

About 40 percent of the fuel consumed in transition economies is used in low-temperature heat supply. Slightly less than half of that heat is directed by district heating systems to residential buildings, public services (schools, kindergartens, hospitals, government agencies), and commercial customers (shops and the like). District heating systems exist in many cities containing more than 20,000 people. In many transition economies a significant share of the building stock (about 20 percent in Hungary) was built using prefabricated concrete panels with poor heat insulation and air infiltration.

Advanced Western technology (automated heat distribution plants, balancing valves, heat mirrors, efficient taps, showerheads, heat-reflecting layers of windows) offers significant potential for more efficient heat use in buildings (Gritsevich, Dashevsky, and Zhuze, 1997). Such technology can save up to 30 percent of heat and hot water and increase indoor comfort. Among the main advantages of Western products are their reliability, efficiency, accuracy, design, and sometimes competitive prices. Some Western companies have launched joint ventures with Eastern European, Ukrainian, and Russian partners or

created their own production lines using local workers. In many cases this seems to be a better option than imports, because underemployed factories and human capital may otherwise induce conflicts of interest.

Many transition economies have developed advanced energy-efficiency technology (powder metallurgy, variable-speed drives for super-powerful motors, fuel cells for space stations, plasmic technologies to strengthen working surfaces of turbine blades). Thus the greatest benefits can be gained when domestic technology and human capital and an understanding of local conditions are combined with the best Western technology and practices.

Developing countries

Many developing countries do not have the infrastructure needed to study and evaluate all the technological options that might suit their needs.

Despite the many positive implications of transferring energy-efficient technology, some major issues need to be addressed to fully exploit the potential benefits to developing countries (UNDP, 1999):

- ***Proper technology assessment and selection.* The technology transfer process must help user enterprises evaluate their technological options in the context of their identified requirements (TERI, 1997a). Developing countries are at a great disadvantage in selecting technology through licensing. Companies develop technology mainly to suit their current markets; technology is not necessarily optimised for the conditions in recipient countries. Many developing countries do**

not have the infrastructure needed to study and evaluate all the technological options that might suit their needs. Moreover, an enterprise trying to sell a technology to a developing country will rarely give complete and unbiased advice. So, there is an urgent need to develop an information support system and institutional infrastructure to facilitate the selection of appropriate technologies. In India, for example, a Technology Development Board was established in 1996 to facilitate the assimilation and adaptation of imported technology (CMIE, 1997).

- ***Adaptation and absorption capability.*** **Technology transfer is not a one-time phenomenon. The transferred technology needs to be updated from time to time, either indigenously or through periodic imports. Moreover, lack of local capability can result in the transferred technology seldom reaching the designed operational efficiency, and often deteriorating significantly. This raises the need for local capacity building to manage technological change. In a narrower sense, this could be facilitated by policies requiring foreign technology and investment to be accompanied by adequate training of local staff (President's Committee of Advisors on Science and Technology, 1999).**

- ***Access to state-of-the-art technology and to capital.*** **In many cases transferred technology is not state of the art, for several reasons. First, enterprises in industrialised countries need to recover the costs of technology development before transferring the technology to other countries, introducing a time lag in the process. Second, in some developing countries there is a demand lag for the latest technology due to factors such as lack of capital or trained staff. Third, there are inappropriate technology transfers because of the higher costs of acquiring state-of-the-art technology. A lack of capital and strong desire to minimise investment costs have often led developing countries to import obsolete used plants and machinery.**

- ***The problems of small and medium-sized enterprises.*** **Small industrial enterprises account for a large share of energy and technology use in many developing countries. These enterprises may play an important role in the national economy but generally remain isolated from or ignorant of the benefits of technology upgrading. For such enterprises, where off-the-shelf solutions are seldom available, knock-down technology packages from industrialised countries are rarely possible. An important element of technology transfer for this group is proper competence pooling to arrive at appropriate technology solutions.**

Again, the situation differs between higher- and lower-income developing countries. Several countries in Latin America and Southeast Asia are producing highly efficient technology and vehicles - electrical motors, refrigerator compressors, cars - through local companies or subsidiaries of multinational companies. Control systems, super-efficient windows, and new materials that improve the thermal insulation of buildings may offer further opportunities for technology transfer to higher-income developing countries (Hagler Bailley Services, 1997).

Types of potential for increased energy efficiency

As noted, the global energy efficiency of converting primary to useful energy is estimated to be 37 percent.[6] But the useful energy needed for a desired energy service will likely fall. Estimated improvements are based on known technologies, expected costs, consumer behaviour, market penetration rates, and policy measures. When considering the potential for increased energy efficiency, it is essential to distinguish between several types of potential, each describing future technological achievements with different time horizons and boundary assumptions (as well as level of analysis in the case of economic potential). This report uses the following definitions (Enqute Commission, 1991; IEA; 1997a; figure 6.4):

- **The theoretical potential represents achievable energy savings under theoretical considerations of thermodynamics where energy services (such as air conditioning and steel production) are kept constant but useful energy demand and energy losses can be minimised through process substitution, heat and material reuse, and avoided heat losses (see section below on theoretical potentials after 2020).**

- **The technical potential represents achievable energy savings that result from implementing the most energy-efficient commercial and near-commercial technology available at a given time, regardless of cost considerations and reinvestment cycles. This can be expressed as a phased-in potential that reflects the total replacement of existing energy-converting and -using capital stocks.**

- **The market trend potential - or expected potential - is the efficiency improvement that can be expected to be realised for a projected year and given set of boundary conditions (such as energy prices, consumer preferences, and energy policies). The market trend potential reflects obstacles and market imperfections that keep efficiency potentials from being fully realised (see the section below on obstacles).**

- **The economic potential is the energy savings that would result if during each year over the time horizon in question, all replacements, retrofits, and new investments were shifted to the most energy-efficient technologies that are still cost-effective at given energy market prices. It also includes all organisational measures such as maintenance, sensitive operation and control, and timely repairs. The economic potential has subdefinitions depending on the economic perspective being used: the business (or project) perspective, the macroeconomic perspective, or the societal (or welfare-based) perspective (box 6.2). The economic potential implies a well-functioning market, with competition between investments in energy supply and demand. It also assumes that the barriers to such competition have been corrected by energy policies. It is assumed that as a result of such policies, all**

users have easy access to reliable information about the cost-effectiveness and technical performance of existing and emerging options for energy efficiency. The transaction costs for individual investors, and the indirect costs of policies associated with implementing these options, are assumed to have been lowered to their irreducible minimum.

- **The societal (or welfare-based) potential represents 'cost-effective' savings when externalities are taken into consideration. These include damage or avoided damage costs from health impacts, air pollution, global warming, and other ecological impacts, as well as energy-related occupational accidents that accrue to society. This wider definition of cost-effectiveness is the most important for a holistic energy policy that includes energy security and environmental quality (OTA, 1993).**

- **Finally, the policy-based achievable potential represents the energy savings that can be realised with various policy instruments or packages of policy instruments. Here field data are used to estimate participation rates and per participant savings in voluntary or standards-based technology programmes. The policy-based achievable potential lies between the market trend potential and the economic potential (which can be influenced by energy taxes).**

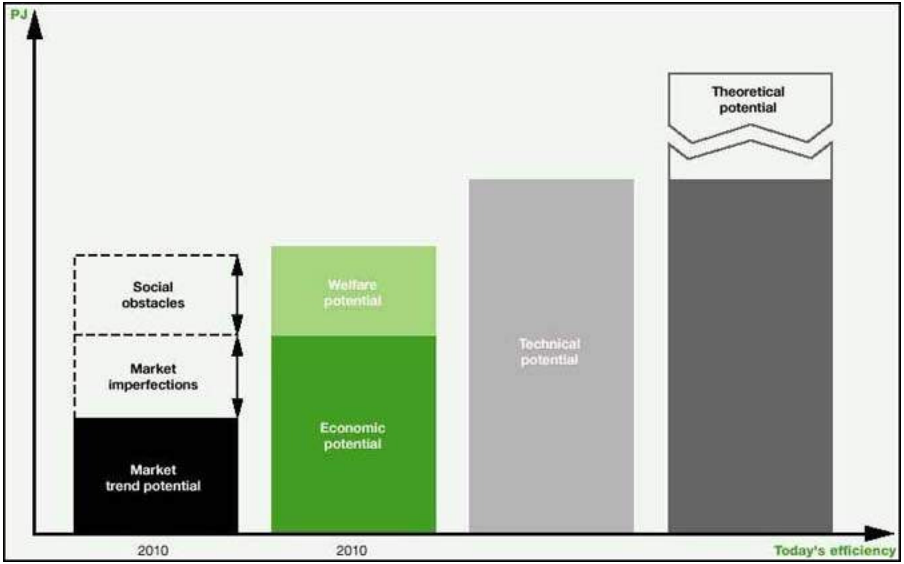


FIGURE 6.4. THEORETICAL, TECHNICAL, ECONOMIC, AND MARKET TREND POTENTIALS OF ENERGY EFFICIENCY

Source: Enqute Commission, 1991.

BOX 6.2. DIFFERENT PERSPECTIVES ON THE ECONOMIC POTENTIAL OF ENERGY EFFICIENCY

In all definitions of the economic potential of energy efficiency, the core cost-effectiveness test is the life-cycle cost of providing a given level of energy services. Different definitions of the economic potential arise because of different cost-benefit perspectives. These perspectives influence how costs and financial parameters are defined and whether policy-dependent implementation costs or reductions in external costs are included.

The economic potential at the business level is calculated from the perspective of an individual investor based on engineering and economic life-cycle costs, using a financial perspective. In this narrowest of all definitions, total costs consist of the levelised capital costs of energy efficiency investments plus changes in annual energy and non-energy operation and maintenance costs. Neither the costs of large-scale policy implementation nor the cost savings from policy-induced feedback effects are attached to this potential. The discount rate for evaluating the cost-effectiveness of energy efficiency investments is typically set to reflect the costs of capital of particular sectors, industries, or households. After-tax energy efficiency investments are compared to after-tax average energy prices as projected for each sector or group of energy users.

The macroeconomic potential is based on a more comprehensive accounting of costs and on a different financial perspective. Here the administrative costs of implementing various required policies are included. In addition, energy efficiency investment costs and policy implementation costs are corrected in a forward-looking manner to account for changes in manufacturer pricing strategies, economies of scale, and learning effects.

Achieving two benefits of increased energy efficiency - positive economic effects and reduced environmental burden - is called a 'double dividend'.

This chapter focuses on the economic potential. The economic perspective underlying the potentials reported here, however, varies by study. Most current estimates are based on a business (financial) perspective, though there are also hybrids that use a macroeconomic perspective (see box 6.2). Quantitative comparisons between business and macroeconomic efficiency potentials suggest that microeconomic approaches

underestimate the cost-effective savings potential (Krause, 1996). Similarly, macroeconomic approaches underestimate cost-effective savings potentials relative to a societal perspective.

The economic potential of energy efficiency by region and sector

Economic potentials of energy efficiency depend on current and foreseeable technology developments and on current and anticipated energy prices (box 6.3). In a world of low energy prices, the potential is relatively small. But high energy prices could be achieved through energy taxes at a national, regional, or global level. The economic potential presented below for each region is based on the energy prices assumed in the literature. Calculations of the economic potential of energy efficiency cover different technologies:

- **The potential of mono-functional and concise energy-converting technology (boilers, heat exchangers, electrical motors) is usually determined by standard profitability calculations comparing the full costs of alternative and statistically relevant conversion technology.**

- **Process substitution and new building concepts or transportation systems include other changes in economic efficiency (capital, labour, and so on) and in product or service quality. Here it becomes difficult to talk about the profitability of the technology in the narrow sense of energy efficiency if the new, higher-efficiency technology is considered competitive in the broader sense (as with new catalysts in the production of petrochemicals, separation by membranes instead of energy-intensive distillation, or low-energy houses instead of conventional houses).**

- **Branch-specific but technology-clustered energy efficiency potentials of low energy-intensive sectors in industry or the commercial sector are estimated by trend extrapolation of statistical data or by generalisation of calculations made for representative or typified plants or factories. To avoid misinterpretation, data on** branch-specific energy efficiency potentials should not include intrabranch structural changes (such as a shift of high value added but low energy-intensive pharmaceuticals to higher shares of total value added in the chemical industry).

These different cost assessments may help explain the differences in certainty about the economic potentials cited below. The data on economic potentials provide projections for 2010 and 2020. This means that where reinvestment cycles last more than 20 years (as with buildings, public transport, and plants of basic product industries), the economic potentials are only partly realised by 2020. The sectors and technological areas discussed in this section were chosen based on the relevance of the efficiency technology and the availability of the literature for the region or country considered.

Deviations from a given economic potential reflect changes in energy prices, economies of scale, or local differences. In many cases the life-cycle cost functions have rather broad minima (such as optimal insulation thickness), which means that there is little risk of overinvesting in energy efficiency or of overestimating the cited potentials.

Western Europe

Industry. Until the early 1990s industry was the largest consumer of final energy in Western Europe.[8] But despite production growth of about 2 percent a year, the final energy demand of Western European industry has hovered near 11,500 petajoules for the past 20 years. Yet industry still holds substantial economic efficiency potential, even in energy-intensive sectors where investment has focused on efficiency improvements to lower high energy costs (Phylipsen, Blok, and Worrell, 1998).

- De Beer (1998, pp. 75-102) estimates that by 2020 paper mills operating with new pressing and drying techniques, latent heat recovery systems, and a number of minor improvements (closed water circulation, graduated heat recovery) will have

50 percent lower specific heat demand and that investment costs may be lower than for conventional paper-making (table 6.4). The economic efficiency potential of steel-making is less extraordinary, between 13 and 20 percent, and results from thin slab casting, more efficient blast furnaces, and minor improvements in the oxygen steel process by 2020 (Jochem and Bradke, 1996). Similar economic efficiency potential has been described for refineries (Refining Processes, 1998), petrochemical processes (Patel, 1999) and basic organic chemicals (Brewer and Lopez, 1998), construction materials (Rosemann and Ellerbrock, 1998; Ottoboni and others, 1998), glass production (ATLAS, 1997), and the food industry (Jochem and Bradke, 1996).

- **For Dutch light industry, the economic efficiency improvements in 2000 (relative to 1990) are estimated at 30 percent (with a 5 percent discount rate) and 27 percent (with a 10 percent discount rate; Blok and others, 1996; Bde and others, 1999).**

- **Baumgartner and Muggli (1996) evaluated the efficiency improvements of cross-cutting technologies in Swiss industry. Savings of 15-35 percent were found for electrical and mechanical drives over the next 10-15 years (Almeida, Bertoldi, and Leonhard, 1997). Metering, controlling, and optimal regulation can lead to efficiency improvements of up to 15 percent in most industrial processes. Cogeneration in Western Europe still holds economic potential, particularly with the midterm effects of liberalising electricity supply and small cogeneration (ATLAS, 1997; EC, 1999).**

Residential. The economic efficiency potential in heating of residential buildings depends - besides regional aspects - on the stock of boilers and their reinvestment cycles, the rate of constructing new buildings, and the rate of refurbishing existing buildings. Condensing boilers are about 10 percent more energy efficient than a new low-temperature boiler and

15-25 percent more efficient than existing boilers (Ziesing and others, 1999). Insulation of building elements, highly efficient window systems, and adequately thick insulation are economic within the cycle of refurbishment (ETSU, 1994).In new buildings, low-energy houses (those with annual heat demand of 50-100 kilowatt-hours per square metre) are now cost-effective due to better design and low-cost insulation techniques and window sytems (Altner and others, 1995).

BOX 6.3. ECONOMIC BENEFITS OF INCREASED ENERGY EFFICIENCY IN END USES - THE UNKNOWN DOUBLE DIVIDEND

Energy consumers benefit when profitable energy efficiency potentials are realised.[7] But the economy also benefits, because saved energy costs can be reallocated, energy imports are replaced (in many countries) by domestically produced energy-efficient products and (energy) services, and labour-intensive branches can grow in industry, construction, and services (instead of capital-intensive energy supply), spurring innovation. Macroeconomic analyses for Germany and the United States show that policies to improve energy efficiency and to shift to advanced technology and less carbon-intensive fuels generate four important benefits for the national economy (Jochem and Hohmeyer, 1992; Laitner, Bernow, and DeCicco, 1998). Such policies:

- Spur economic growth to a small degree (by less than 1 percent of the absolute growth rate of GDP) due to the reallocation of saved energy costs.
- Generate jobs (including entrepreneurial jobs that foster resourceful, self-sufficient, and satisfied workers) for the reasons mentioned above. Net employment increases by 40-60 new jobs per petajoule saved each year.
- Increase exports of high-technology products. In 1976-92 exports of 12 energy-efficient products increased more than 50 percent faster than West Germany’s total exports.

- Reduce the environmental and social costs of energy use that were previously uncounted in market transactions for fuel. Such costs may be as high as $0.02 per kilowatt-hour of electricity (Friedrich and Krewitt, 1997) and almost $0.01 per kilowatt-hour of oil product used, not including the impacts of climate change (Hohmeyer, Ottinger, and Rennings, 1997).

Achieving two benefits of increased energy efficiency - positive economic effects and reduced environmental burden - is called a ‘double dividend’. Unlike many other employment effects of investment, the jobs created by efficiency investments are not evenly distributed over time. In most cases they are created during the initial period of investment - when wall insulation is installed or investments are made in condensing boilers or high-efficiency window systems. In addition, the regional distribution of net employment becomes more equitable. Employment in the energy supply sector is concentrated in urban and industrial areas, while efficiency involves planners, crafts, trade, and banking in the entire country.

TABLE 6.4. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN WESTERN EUROPE, 2010 AND 2020

Sector and technological area	**Economic potential (percent)[a]**		**Energy price level assumed**	**Base year**	**Source**
	2010	**2020**			
Industry					
Iron and steel, coke ovens	9-15	13-20	1994	1995	Jochem and Bradke, 1996; Ameling and others, 1998
Construction materials	5-10	8-15	1997	1997	
Glass production	10-15	15-25	1997	1997	ATLAS, 1997

Refineries	5-8	7-10	1995	1997	*Refining Processes,* 1998
Basic organic chemicals	5-10		1997	1996	Patel, 1999; Brewer and Lopez, 1998
Pulp and paper		50	1996	1997	De Beer, 1998
Investment and consumer goods	10-20	15-25	1994	1995	Jochem and Bradke, 1996; Bde and others, 1999
Food	10-15		1997	1997	Jochem and Bradke, 1996
Cogeneration in industry		10-20	1997	1997	ATLAS, 1997; EC, 1999
Residential					
Existing buildings					
Boilers and burners	15-20	20-25	today’s prices	1997	ETSU, 1994; Bde and others, 1999
Building envelopes	8-12	10-20	today’s prices	1995	Ziesing and others, 1999
New buildings		20-30	today’s prices	1995	Altner, Durr, Michelson, 1995
Electric appliances	20-30	35-45	1997	1997	GEA, 1995; ECODROME, 1999; Hennicke and others, 1998; Boardman and others, 1997
Commercial, public, and agriculture					
Commercial buildings	10-20	30	8-13 cts/kWh	1995	Geiger and others, 1999
Electricity	10-25	20-37	4-10 cts/kWh	1997	ECODROME, 1998

Heat		15-25	today’s prices	1998	Zeising and others, 1999
Public buildings		30-40	7-15 cts/kWh	1992	Brechbhl, 1992
Agriculture and forestry		15-20	today’s prices		Neyer and Strebel, 1996
Horticulture		20-30	today’s prices		Arbeitsgemeinschaft, 1992
Decentralised cogeneration		20-30	today’s prices	1995	Ravel, 1994
Office equipment		40-50	1995	1995	Aebischer and others, 1996; MACEBUR, 1998; Hallenga and Kok, 1998
Transportation					
Cars	25		today’s prices	1995	IPSEP, 1995
Door-to-door integration	4			1995	Zeising and others, 1999
Modal split of freight transport		3[b]		1995	
Trains and railways		20	today’s prices	1999	Brunner and Gartner, 1999
Aircraft, logistics	15-20	25-30	today’s prices	1998	IPCC, 1999a

a. Assumes a constant structure or use of the sector or technology considered. b. Refers to the final energy use of the entire sector.

The economic efficiency potential of electric appliances in 2010 is best evaluated by comparing the equipment in use with the equipment available on the market. But the market is not homogeneous: a survey of washing machines, dryers, and dishwashers available in the European Union showed minimum:maximum ratios of specific

consumption between 1:2.5 for washing machines and 1:4 for condenser tumble dryers (GEA, 1995). Initial costs are sometimes higher for efficient equipment, but life-cycle costs are generally lower. In France a detailed end-use study showed that electricity savings of 40 percent can be achieved by replacing average equipment with the most efficient appliances readily available on the market (Rath and others, 1997; ECODROME, 1998). These results are confirmed by Hennicke and others (1998) and Ziesing and others (1999). Given the relatively short lives of lights and appliances, savings of 33 percent could be achieved in the United Kingdom by 2010 with the widespread adoption of better lights and appliances using known technologies (Boardman and others, 1997).

Service and public sectors. In 1990 office equipment consumed just 3-4 percent of the electricity used in Western Europe’s service sector (Aebischer, Schwarz, and Spreng, 1996). But office equipment is the fastest-growing consumer of electricity. About two-thirds of this electricity is used in standby and off modes. Thus easy and cost-effective savings are possible for most equipment (Hallenga and Kok, 1998; MACEBUR, 1998). With the fast increase in the amount of office equipment and its short lives, these improvements could be realised by 2010. Hennicke and others (1998) reports that 27-35 percent of the electricity consumed by Germany’s service sector could be saved for $0.043-0.071 a kilowatt-hour.

The economic potential for reducing space and process heat demand in commercial buildings ranges from 15-25 percent (Ziesing and others, 1999; Aebischer and others, 1996). The efficiency of heat generation and distribution could be improved by 10-15 percent through reinvestmentsin boilers, burners, and insulation and control techniques, in some cases by direct process heat generation (avoiding steam and hot water systems), and by engine-driven cogeneration.

TABLE 6.5. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN NORTH AMERICA, 2010

Sector and	Economic potential	Energy price level	Base year	Source

area	(percent)		assumed		
	United States[a]	Canada			
Industry					
Iron and steel	4-8	29	United States: scenario for price developments[b]	United States: 1995	United States: Interlab, 1997;
Aluminium (primary)	2-4				Brown and others, 1998;
Cement	4-8				Romm, 1999
Glass production	4-8			Canada: 1990	
Refineries	4-8	23	Canada: price scenario by province[c]		Canada: Jaccard and Willis, 1996;
Bulk chemicals	4-9	18			Bailie and others, 1998
Pulp and paper	4-8	9			
Light manufacturing	10-18				
Mining	n.a.	7			
Industrial minerals	n.a.	9			
Residential					
Lighting	53		United States: scenario for	United	United States:

			price developments	States: 1995	Interlab, 1997;
Space heating	11-25				Brown and others, 1998;
Space cooling	16				OTA, 1992
Water heating	28-29			Canada: 1990	
Appliances	10-33		Canada: price scenario		Canada: Bailie and others, 1998
Overall		13			
Commercial and public					
Space heating	48		United States: scenario for price developments	United States: 1995	United States: Interlab, 1997;
Space cooling	48				Brown and others, 1998
Lighting	25				
Water heating	10-20			Canada: 1990	Canada: Bailie and others, 1998
Refrigeration	31		Canada: price scenario		
Miscellaneous	10-33				
Overall	n.a.	9			
Transportation					
Passenger cars	11-17		United States: scenario for	United	United States:

			price developments	States: 1997	Interlab, 1997;
Freight trucks	8-9				Brown and others, 1998
Railways	16-25				
Aeroplanes	6-11			Canada: 1990	Canada: Bailie and others, 1998
Overall	10-14	3	Canada: price scenario		

a. Industrial energy efficiency potentials in the United States reflect an estimated penetration potential under different conditions based on the Interlaboratory Working Group on Energy Efficient and Low-Carbon Technologies (1997). There are no separate estimates available for the economic potential. The economic potential under business-as-usual fuel price developments is estimated at 7 percent in energy-intensive industries and 16 percent in light industries. b. The Inter-Laboratory Working Group study (1997) used price scenarios for 1997-2010 to estimate the potential for energy efficiency improvement, based on the *Annual Energy Outlook 1997* scenario (EIA, 1996). The scenario assumes a 1.2 percent annual increase in oil prices from 1997 levels. c. For comparison; in 2010 light fuel oil prices are $6-8 a gigajoule at the 1999 exchange rate (Jaccard and Willis Energy Services, 1996).

Transportation. Between 1990 and 2010 final energy use by transport may increase by 40 percent in Western Europe if no efficiency potentials are used. About 50 percent of this energy is used by passenger cars and almost 40 percent by road freight. A voluntary agreement concluded by the Association of European Car Manufacturers reflects the potential for energy-efficient car use: in 2008 new cars will be 25 percent more fuel efficient than in 1995. Using taxes and insurance to internalise the external costs of road

transport, estimated at $20-70 billion, would increase efficiency by another 7-16 percent.

Relative to road transport, Western Europe's rail transport is about 3 times less energy-intensive for passengers and up to 10 times less energy-intensive for goods. With lighter trains, reduced air drag, and better drive concepts, the specific electricity consumption of rail transport could drop almost 50 percent over the next 40 years (Brunner and Gartner, 1999). A 25 percent cut in railway freight tariffs due to increased productivity and cross-border harmonisation is expected to induce a shift from road to rail, allowing a 3 percent reduction in final energy use for the transport sector as a whole. Although aeroplanes and related logistics have substantial efficiency potential (IPCC, 1999a), it is not expected to compensate for the growth in air transport mileage.

North America

North America - defined here as Canada and the United States, but not Mexico - has higher energy consumption per capita than any other region.[9] Canada and the United States share several characteristics (large size, low energy prices) but also differ substantially (climate). In both countries recent studies have assessed the potential for increased energy efficiency by 2010. In the United States the Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies (1997) assessed the economic potential for efficiency improvement, while a recent follow-up study assesses the potential impact of policies. In Canada a study has assessed several industrial sectors in detail (Jaccard and Willis Energy Services, 1996), while others have assessed the economic potential of sets of technologies in all sectors (Bailie and others, 1998; Brown and others, 1998; Faruqui and others, 1990; OTA, 1991). Both countries are assessing policies to address climate change, and the results may vary from previous studies (table 6.5).

Under the business-as-usual scenario, energy growth in the United States through 2010 would increase energy demand by 26 percent relative to 1990. Two other scenarios

address, with progressively stronger measures, the adoption of energy-efficient technologies. The first, the efficiency scenario, assumes that technology-based reductions in energy and carbon emissions become cost-effective and so attractive to the marketplace. The second, the high-efficiency/low-carbon scenario, assumes that the United States makes an even greater commitment to reducing carbon emissions through federal and state programs and policies, as well as active private sector involvement. The high-efficiency/low-carbon scenario assumes that the emission charge is $25 or $50 per tonne of carbon.

Industry. Because of the complexity of industrial processes, the Interlaboratory Working Group did not model from the bottom up using explicit estimates of changes in efficiency expected from the introduction of energy-efficient technologies. Instead, the group used existing models to estimate the potential for increased general investment in industrial energy efficiency, supplemented by examples of a few technologies that have potential throughout the industrial sector (for example, advanced gas turbines and efficient motors). The models single out seven energy-intensive industries that together account for 80 percent of manufacturing energy use. Light manufacturing is considered a separate category.

Under the business-as-usual scenario, manufacturing grows 2.1 percent a year through 2010, divided between energy-intensive industries (1.3 percent a year) and non-intensive industries (2.6 percent a year). Total energy intensity is projected to decline by 1.1 percent a year (Interlaboratory Working Group, 1997).

In the efficiency scenario, industrial energy consumption drops 6.6 percent relative to the business as usual scenario. In the high-efficiency/low-carbon scenario, consumption falls 12.5 percent. Energy efficiency improvements are larger in light industry than in heavy manufacturing because there are more opportunities to adopt energy-efficient-technologies. Energy is a smaller component of overall manufacturing costs, so there is

less incentive to adopt new technology than in the past. A recent bottom-up study (Worrell, Martin, and Price, 1999) of energy efficiency potential in the U.S. iron and steel industry estimates the potential contribution of nearly 50 technologies, and suggests that the potential is twice as high as indicated by the Interlaboratory Working Group study.

Between 1990 and 2010 final energy use by transport may increase by 40 percent in Western Europe, if no efficiency potentials are used.

Bailie and others (1998) estimate at 8 percent the cost-effective potential for reducing carbon dioxide (CO_2) emissions through increased energy efficiency in Canadian industry.

The authors use high discount rates to reflect the market rates of time preference.[10] Jaccard and Willis Energy Services (1996) estimate the economic and technical potential for increased energy efficiency in six major industrial sectors using the same model and a discount rate of 7 percent in assessing the macroeconomic potential (see box 6.2). They find technical potential in 2010 to vary by industry from 8 to 38 percent (relative to 1990), while economic potential varies from 7 to 29 percent. These findings are similar to those for Western Europe (see table 6.4).

Buildings. In the efficiency scenario, buildings use 36.0 exajoules of energy in 2010, compared with 38.0 exajoules in the business as usual scenario. The efficiency scenario assumes that by 2010 buildings will have achieved just over one-third of their cost-effective energy efficiency savings potential of 15 percent (Interlaboratory Working Group, 1997). Energy services cost $11 billion a year less than in the business-as-usual scenario. Costs are lower because the decrease in energy spending that results from installing more efficient technology is larger than the cost of purchasing and installing this

technology in buildings. The high-efficiency/low-carbon scenario assumes that nearly two-thirds of the cost-effective energy efficiency savings are achieved by 2010. The result is a larger drop in energy use, to 33.3 exajoules - or by 13 percent relative to the business-as-usual scenario.

Bailie and others (1998) assume that energy efficiency measures are implemented in Canadian buildings. While households show moderate economic potential (13 percent), the economic potential for commercial buildings is limited (9 percent).[11] Although the technical potential is high (Bailie and others, 1998), the assumed high costs and additional office automation lead to smaller economic potentials.

Transportation. The business as usual scenario for U.S. transportation assumes that the passenger car fuel efficiency rate (in litres per 100 kilometres) will improve from 8.55 in 1997 to 7.47 in 2010. But this represents a 1.4 percent annual increase in fuel economy, an improvement that has not been seen in the past without increased fuel mileage standards or higher oil prices. The business-as-usual scenario also assumes that the fuel efficiency of light trucks will not increase. The result is an increase in transportation energy use from 26,000 petajoules in 1997 to 34,000 petajoules in 2010 despite a 10 percent improvement in overall efficiency. Under the efficiency scenario, transportation energy use is 10 percent lower in 2010. Under the high-efficiency/low-carbon scenario, it is 14 percent lower (Interlaboratory Working Group, 1997).

The high-efficiency/low-carbon scenario includes the efficiency scenario assumptions as well as major breakthroughs in fuel cells for light-duty vehicles, large gains in the energy efficiency of aircraft, and an optimistic estimate of the cost of ethanol fuel from biomass. This modelling approach is very different from that taken for buildings, because of the assumption of breakthrough technology in transportation.

Bailie and others (1998), however, estimate an extremely low economic potential for

energy efficiency improvement in Canada's transportation sector.[12] The study concentrates on efficiency standards for engines but also includes fuel switching. The baseline scenario assumes large growth in transport demand, dramatically increasing energy demand in Canada between 1990 and 2010. The study finds a large technical potential for efficiency improvement, but the costs of the economic potential are prohibitive. Hence the economic potential is estimated at just 3 percent relative to 2010 baseline energy use.

Japan and Southeast Asia

The literature on energy efficiency potentials in Japan and Southeast Asia is somewhat limited (table 6.6).[13] Although the region has a relatively young capital stock, economic efficiency potentials are still quite high. This is due to intensive technological innovations and relatively high energy prices (Rumsey and Flanagan, 1995a).

Between 1975 and 1995 primary energy demand more than quadrupled, shifting the centre of the energy market from the Atlantic Basin to the Pacific Basin (Fesharaki, 1998). Hence energy efficiency is a paramount policy objective. The Asia Least Cost Greenhouse Gas Abatement Strategy (ADB, GEF, and UNDP, 1998) cites cumulative potentials for 2010 and 2020.

Industry. Goto (1996) estimates industrial energy efficiency improvements through 2010 for several energy-intensive branches in Japan (see table 6.6). The energy savings for iron and steel range from 10-12 percent, for chemicals from 5-10 percent, for cement production from 2-8 percent, and for pulp and paper from 6-18 percent (box 6.4). For Southeast Asia, ADB, GEF, and UNDP (1998), IIEC (1995), Adi (1999), Ishiguro and Akiyama (1995), and the Viet Namese government find that similar savings are possible in 2010 and 2020.

Residential, commercial, and public sectors. The energy savings potential of residential and commercial uses could be untapped with various demand-side management programmes for air conditioning, refrigeration, lighting, and cooling. Some 300-450 petajoules a year could be gained in Japan’s residential sector by insulating existing buildings within their reinvestment cycle. IIEC (1995) reports savings of 20-60 percent for electric appliances.

TABLE 6.6. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN JAPAN AND SOUTHEAST ASIA, 2010 AND 2020

Sector and area	Economic potential (percent or petajoules a year)[a]		Energy price level assumed (U.S. cents per kilowatt-hour)	If percent, base year	Source
	Japan 2010	**Southeast Asia 2020**			
Industry					Japan: Goto, 1996; JISF, 1993
Iron and steel	10-12%		0.2	1990-95	Southeast Asia: Ishiguro and
Cement	2-8%		2-20	1990-95	Akiyama, 1995; ALGAS, 1998,
Chemicals	5-10%		0.4-7.8	1990-95	IIEC, 1995; Adi 1999; Government
Pulp and paper	6-18%		1.5-3.3	1990-95	of Viet Nam;

					Nguyen
Electric motors		20%	1998 prices	1995	Thuong, 1998; Aim Project
Total industry		**2,017 PJ**	**1998 prices**	**1998**	Team, 1994
Residential					Kaya and others, 1991; IIEC,
Existing buildings					1995; ALGAS, 1998;
50-100 millimetre insulation	290-450 PJ		2.0-8.5	1995	Wanwacharakul, 1993
Electric appliances	20-60%	20-60%			
Illumination	20-75%	20-60%			
Commercial and public sectors					IIEC, 1995; ALGAS, 1999
Buildings 50-100 millimetre insulation	240-280 PJ	293 PJ	2-5	1991,92	
Transportation		**2,275 PJ**		**1992**	IIEC, 1995
Compact cars	1.8%		0.044	1990	Japan: Goto, 1996;
Buses	0.2%		0.196	1990	Aim Project Team, 1994

Trucks	2.8%		0	1990	
Compact cargo vehicles	13.7%		0	1990	
Within cities					
Vehicles	7%		0.01-0.06	1990	
Buses, trucks cargo vehicles	14%		0.01-0.06	1990	
Passenger cars	0.3%		0.06	1990	

a. Assuming constant structure or use of the sector or technology considered.

BOX 6.4. JAPANESE COMPANIES GO AFTER OPPORTUNITIES

Hitachi city district heating system. Energy displacement between industry and buildings entails the use of residual heat from a cement factory for district heating and cooling in Hitachi city covering a total area of 12.5 hectares. Some 107,000 square metres of floor area will be covered by the district heating system, with a maximum supply capacity of 8.93 gigawatts of heat and 11.9 gigawatts of cooling. When the system produces a surplus of heat, the excess heat is used for electricity production with a 373 kilowatt-hour generator (Kashiwagi, 1994).

Iron and steel. Efficient ignition of a sintering furnace for crude steel production is possible through installed segregation equipment, slit burners, and changes in waste heat recovery - for savings of 56.5 gigajoules a year. Ignition fuel was reduced by 70 percent with a payback period of 1.6 years at 1986 prices (CADDET, 1997).

Cogeneration. The Jujo Kimberly K.K cogeneration power plant for a paper mill uses an aeroengine-driven gas turbine with an output of 7,600 kilowatts of electricity and 20 tonnes per hour of steam, meeting 70 percent of the mill’s electricity requirements. The system attains an overall efficiency of 81 percent, with a payback of four years. Energy costs were cut 30 percent, and labour costs 20 percent. The space saves confers an additional economic benefit.

In the commercial and public sectors the same efficiency technology would save 240-280 petajoules a year. Mungwitikul and Mohanty (1997) report electricity savings of 25 percent for office equipment at no additional cost in Thailand.

Transportation. In 1980-95 transport was the largest consumer of energy in Japan and Southeast Asia, with annual growth of 8.8 percent (excluding Viet Nam). Transport energy demand is still increasing because larger vehicles are becoming more popular, while the share of small vehicles in new car sales fell to 60 percent in 1996. Japanese government policy is now aiming to introduce the ‘top runner method’, setting efficiency standards above the performance standards currently achievable in order to raise vehicle fuel efficiencies. These measures include subsidies for hybrid vehicles, which double fuel efficiencies. Smaller cars are expected to reduce their fuel consumption to 3.0-3.6 litres per 100 kilometres, and one car manufacturer plans to increase efficiency by 25 percent between 1995 and 2005.

Energy policy also attempts to improve the energy efficiency of trains, ships, and planes, upgrading distribution efficiency by promoting railroad transportation, coastal shipping, and public transport. A study on an electric mass transit project under construction in Thailand identified potential savings of 28 petajoules a year. The savings would come from switching to diesel fuel in city buses. The introduction of fuel cells in road vehicles will further improve efficiency after 2010.

TABLE 6.7. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN EASTERN EUROPE, 2010

Sector and area	Economic potential (percent)	Energy price level assumed	Base year	Source

Industry				
Pig iron	3	EU, 1995		Ministry of Industry, Poland, 1990
Electric steel	10	EU, 1995		
Hot rolled products	32	EU, 1995		
Ferrous metallurgy	24	EU, 1995		
Electrolytic copper	15	EU, 1995		
Aluminium	24	EU, 1995		National Energy Agency, Bulgaria, 1998
Non-ferrous metals	4	EU, 1995		
Chemical products	31	EU, 1995	1995	
Synthetic fibres	12	EU, 1995		
Building materials	48	EU, 1995		
Cement dry	16	EU, 1995		
Leather, footwear	4	EU, 1995	1995	
Timber, wood industry	5	EU, 1995	1995	
Food industry	23	EU, 1995	1995	
Machine manufacturing	22	EU, 1995	1995	
Construction industry	24	EU, 1995	1995	
Residential				
Existing stock	25	EU, 1995	1995	IEA, 1999

New buildings	30	EU, 1995	1995	
Electric appliances	25	EU, 1995	1995	
Commercial/public				
Heating	25		1995	IEA, 1999
Office equipment	20		1995	
Lighting	40	EU, 1995	1995	
Agriculture				
Heating, drying	22	EU, 1995	1995	IEA, 1999
Electricity	15	EU, 1995	1995	
Transportation				
Cars	20	EU, 1995	1995	IEA, 1999
Public transportation, cities	15	EU, 1995	1995	
Railways	25	EU, 1995	1995	
Air transport	22	EU, 1995	1995	

Eastern Europe

Economic restructuring is playing a decisive role for the energy system and its efficiency path in Eastern Europe, because the drivers of economic policy are now totally different from those under central planning.[14] Under communist rule a standing ambition for expansion led to a very old capital stock with low energy efficiency for basic industries, buildings, and the energy industry itself. Because the region started the transition from an extremely weak social and financial position, the economic crisis - an unavoidable element

of large-scale restructuring - influences voters (Levine and others, 1991).

As a result governments (who wish to remain in power) are often reluctant to take the restrictive steps needed for economic restructuring in general and energy pricing in particular. Countries starting from a better position (Czech Republic, Hungary, Poland, Slovakia, Slovenia) can take the painful steps earlier. Because statistical systems and aggregation practices differ considerably among transition economies and future developments are uncertain, the data on economic efficiency energy potential in table 6.7 should be viewed only as cautious estimates. The data may be subject to major changes when more empirical data become available.

Industry. Specific energy consumption and related efficiency potentials are related to physical production in energy-intensive industries. The economic potential of other sectors ranges from 4 percent (leather) to 40 percent (building materials) by 2010 (see table 6.7). Available data are from climatically and economically different countries (from Bulgaria to Poland) but most of the figures are similar - reflecting a shared history of Soviet technology and standards.

Residential. Individual heat metering in multifamily houses in Eastern Europe represents an energy efficiency potential of at least 15-20 percent. In panel-built housing estates, individual metering of domestic warm water consumption has already resulted in savings of up to 40 percent where it has been introduced. A programme to improve thermal insulation in these buildings began in the mid-1990s with central support. Thus a 20-30 percent reduction of the heat demand in these buildings can be achieved in the next 10 years.

For 2020 and beyond, specific energy and material demands are expected to be close to the EU average. Economic and technology development in Eastern Europe will likely be carried out through the expansion of multinational companies, integration with the

European Union, and globalisation. As a consequence, by 2020 technologies will be in place that are technically and economically acceptable and comparable to EU standards. Exceptions will be some parts of the non-refurbished building stock.

Commercial and public sectors. Improved boilers and heating systems, insulation, high-efficiency window systems, and new lighting systems will contribute to substantial savings in the commercial and public sectors.

Transportation. Although specific energy consumption will likely fall by at least 1 percent a year, the final energy consumed by road transportation will substantially increase due to motorization in Eastern Europe.

Russia and other members of the Commonwealth of Independent States

Members of the Commonwealth of Independent States face very different climates, domestic energy resources, and levels of industrialisation and motorisation.[15] The last extensive studies of economic energy efficiency potentials for the former Soviet Union were performed in the early 1990s (WBNSS, 1999). About 120 technologies and energy-saving measures with potential savings greater than 5.8 petajoules a year were considered, covering all the sectors and assuming the replacement of technology and equipment in use at that time with best-practice, world-class technology (CENEf, 1993). Potential savings were estimated at 21,690 petajoules a year, about 77 percent of which was considered economical by 2005.

TABLE 6.8. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN RUSSIA AND UKRAINE, 2010

Sector and technological area	Economic potential (percent or petajoules a year)		Energy price level assumed	If percent, base year		Source
	Russia	Ukraine		Russia	Ukraine	

	Russia	Ukraine		Russia	Ukraine	
Industry	**3,370-4,980 PJ**	**1,430-2,485 PJ**	1990s price levels of Western Europe	1995	1990	Russia: Federal Ministry of Fuel and Energy, 1998
General	1,524-2,198 PJ			1995		Ukraine: ARENA-ECO, 1997; Vakulko/Zlobin, 1997
Metallurgy	733-1,026 PJ	284-361 PJ		1995	1990	
Iron and steel, coke ovens	132-161 PJ			1995		
Construction materials	440 PJ					
Cement	176 PJ			1995		
Refineries	176-205 PJ	73-138 PJ[a]		1995	1990	
Basic organic chemicals	176-322 PJ			1995		
Pulp and paper	176-322 PJ			1995		
Investment goods industry	322-469 PJ	247-249 PJ		1995	1990	
Electricity savings	More than 30%			1997		
Food industries		114-205				

Food industries		114-205 PJ				
Commercial and public sectors and agriculture			1995 price levels of European Union			Bashmakov, Gritsevich, and Sorokina, 1996; ARENA-ECO, 1997; Lapir, 1997
Commercial buildings						
Agriculture	791-879 PJ	91-138 PJ		1995	1990	
Horticulture	Up to 3 times			1997		
Residential	**1,905-2,198 PJ**	**475-570 PJ**[b]	1995 price levels of European Union	1995	1990	Bashmakov, Gritsevich, and Sorokina, 1996; ARENA-ECO, 1997
Automated boilers	20-40%			1995		
Existing building stock	20-30%			1995		
New buildings	381-431 PJ			1995		
Hot water supply	197-276 PJ			1995		
Transportation	**967-1,172 PJ**	**290-293 PJ**	1995 price levels of European Union	1995	1990	Russia: SNAP, 1999; Russian Federation, Ministry of Transport, 1995

Trains	10-15%			1997		

a. Refineries and chemicals. b. Residential and commercial sectors.

BOX 6.5. MARKET FORCES DRIVE MORE ENERGY-EFFICIENT INDUSTRY IN THE COMMONWEALTH OF INDEPENDENT STATES

Automated controls introduced in the processing of petrochemicals reduced electricity consumption per unit of output by 40-65 percent at the Kirishinefteorgsyntez plant in Leningrad oblast. Narrower fluctuations in technological parameters also increased the lives of electric motors, valves, and transmitters (Goushin and Stavinski, 1998).

At one of Russia’s largest ferrous metallurgy plants, Magnitogorski, the energy management department developed and implemented a programme for energy saving and efficiency that took into account the plant’s new market environment. The programme focuses on making better use of internal energy resources. Steam is now used for electric power cogeneration (26 megawatts), and coke gas is used as a fuel at boilers-utilisers and in the drying of containers for transporting iron, replacing 19,000 cubic metres of natural gas (Nikiforov, 1998).

In 1996 Russia and Ukraine - the two largest members of the Commonwealth of Independent States - used 83 percent of the region’s primary energy. The most recent estimate of Russia’s energy efficiency potential was developed in 1997 (Russian Federation Ministry of Fuel and Energy, 1998). It projects savings of 13,000-15,500 petajoules by 2010; 80 percent of these savings are expected in the end-use sector. The most comprehensive recent evaluation of technological and economic potentials for energy efficiency in Ukraine was undertaken by the Agency for Rational Energy Use and Ecology (ARENA-ECO, 1997).

Industry. The economic efficiency potential of industry in 2010 is about 4,000 petajoules a

year (table 6.8). This is equal to about 30 percent of the economic efficiency potential of the entire economy, or more than 30 percent of the projected energy demand for 2010. In ferrous metallurgy, replacing open-heart furnaces with oxygen converters and electric steel furnaces could save 73-88 petajoules a year (box 6.5). Introducing continuous casting on greater scale could save 59-70 petajoules a year. Recycling an additional 10 million tonnes of ferrous scrap would save 290 petajoules a year.

In primary aluminium production it is realistic to cut the use of electric power to 13,200 kilowatt-hours per tonne by using elec-trolysers of greater capacity and introducing automated control of technological parameters. In the production of building materials the transfer of cement clinker production to dry process in the production of bricks and lime and other related measures may cut energy use by 400 petajoules a year. In the chemical industry, replacing obsolete with modern technology in the production of ammonia, olefines, aromates, alcohols, and the like will not only reduce energy intensity to levels comparable to the best world examples (around 200 petajoules in 2010), it will also improve the product mix.

According to Vakulko and Zlobin (1997), the main directions for rational use of electricity in industrial facilities are: installing electricity metering and control devices, practising power compensation, determining the optimal number of working transformers, and making efficient use of lighting and lighting devices, high-efficiency electric drives, electrothermal devices, welding transformers and units, and converters. Ukraine’s energy efficiency potential in industry is similar once adjusted for the smaller country, but are still about 2,000 petajoules a year by 2010 (see table 6.8).

Residential. Better building insulation will reduce heat losses. Overall, by 2010 Russia could save at least 2,000 petajoules a year in its residential sector. Ukraine could save 500 petajoules a year (see table 6.8). Typical for Russian households, a 250-360-litre refrigerator consumes 500-600 kilowatt-hours a year. According to Bashmakov,

Gritsevich, and Sorokina (1996), more energy-efficient refrigerators could save up to 175 petajoules a year by 2010. The efficiency measures in this sector and the commercial sector are very similar to those in Russia (installing new metering and control devices, improving insulation of buildings and heating systems).

Transportation. Russia's Ministry of Transport has adopted several programmes to make the transportation system more efficient, safe, and comfortable (SNAP, 1999). In 1995 the ministry introduced a programme aimed at introducing energy-saving vehicles, optimising the structure of the vehicle stock, developing energy-efficient engines, and introducing energy-saving fuels and lubricants (Russian Federation Ministry of Transport 1995). Among other measures, the programme is expected to increase of the share of diesel-fuelled trucks and buses and modernise aeroplanes and helicopters.

Though there is great potential for economic energy savings, these savings will be difficult to achieve. Russia and Ukraine cannot provide the necessary financial support to industry and municipalities. Current investments in energy-saving measures are so low that less than 10 percent of economic energy saving potential is being reached in the Commonwealth of Independent States (Bashmakov, Gritsevich, and Sorokina, 1996). But this is likely to change with the economic recovery of Russia and Ukraine over the next 10 years.

India

With more than 1 billion inhabitants, India is one of the world's biggest emerging economies.[16] In the 50 years since independence the use of commercial energy has increased by ten times, and in 1996/97 was 10,300 petajoules (GOI, Ninth Plan Document, 1996). But per capita energy consumption is only about 15 gigajoules a year (including non-commercial energy) - far below the world average of 65 gigajoules. Given the ever-widening gap between energy supply and demand in India, and the resource constraint

impeding large-scale energy generation at source, efficient energy use is an extremely important, cost-effective option. Commercial energy use is dominated by industry (51 percent), followed by transportation (22 percent), households (12 percent), agriculture (9 percent), and other sectors including basic petrochemical products (6 percent).

Industry. Indian industry is highly energy-intensive, with energy efficiency well below that of industrialised countries (see table 6.3). Efforts to promote energy efficiency in such industries could substantially reduce operating costs. About 65-70 percent of industrial energy consumption is accounted for by seven sectors - fertiliser, cement, pulp and paper, textiles, iron and steel, aluminium, and refineries. The other areas considered for this report are brick-making, foundries, and industrial cogeneration. Potential efficiency improvements are the result of a bundle of feasible and economic energy-saving options, identified through energy and technology audits (table 6.9, box 6.6).

TABLE 6.9. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN INDIA, 2010

Sector and technological area	Economic potential (percent or units of energy a year)	Energy price level assumed	If percent, base year	Source
Industry				
Fertiliser	12.6 gigajoules per tonne of NH_3	Today's price		TERI and FAI, 1995
Cement	17%	Today's price	1992	TIFAC, 1992
Electrical	17%			
Thermal	27%			
Pulp and paper	20-25%	Today's price	1994	CII, 1994
Textiles	23%	Today's price	1998	TERI, 1999

Iron and steel	15%	Today's price	1998	TERI, 1996a
Aluminium	15-20%	Today's price	1996	TERI, 1996b
Refineries	8-10%	Today's price	1996	Raghuraman, 1989
Brick-making	15-40%	Today's price	1989	TERI, 1997b
Foundries	30-50%	Today's price	1997	TERI, 1998
Industrial cogeneration	3,500 megawatts (sugar)	Today's price	1997	TERI, 1994
Residential				
Lighting	10-70%	Today's price	1996	TERI, 1997c
Refrigerator	25%	Today's price	1996	TERI, 1997c
Air conditioning	10%	Today's price	1996	TERI, 1997c
Agriculture				
Pump sets	25-55%	Today's price	1995	Kuldip and others, 1995
Transportation				
Two- and three-wheelers	25%	Today's price	1995	IIP, 1995
Cars	7.5-10%	Today's price	1992	TERI, 1992
Trains (diesel)	5-10%	Today's price	1997	TERI, 1997c
Trains (electric)	5-10%	Today's price	1997	TERI, 1997c

Residential. Energy consumption in India's residential sector varies widely across low-, medium-, and high-income classes in rural and urban areas. Household demand for

electricity will likely expand rapidly as urbanisation continues and the availability of consumer durables expands with increasing income. About 40 percent of the electricity used by the sector goes to meet lighting demand, followed by 31 percent for fans and 28 percent for appliances (refrigerators, air conditioners, televisions). The economic potential of efficiency improvements was estimated for lighting (up to 70 percent), refrigerators (25 percent), and air conditioners (10 percent; see table 6.9).

Agriculture. The main areas for conserving energy in agriculture are diesel-fuelled and electric pumps, 16 million of which were in operation in 1991/92. The estimated savings potential of 25-55 percent involves avoiding such common drawbacks as improper selection of pumps and prime movers, improper installation, poor pump characteristics, high friction losses in the valves and the piping system, air inflow in the suction pipe, and improper maintenance and servicing.

Transportation. Transportation accounts for almost half of India’s oil product consumption, in the form of high-speed diesel and gasoline (TERI, 1999). Two major structural aspects of transportation are related to energy efficiency. First, the rail-dominant economy of the 1950s gave way to the road-dominant economy of the 1990s, reaching 81 percent of the sector’s energy consumption (TERI, 1997c). Second, inadequate public transport systems and increasing incomes have led to a rapid increase in personalised modes of transport and intermediate public transport, some of which are extremely energy-inefficient.

A large number of two-stroke-engine two-wheelers are used as personal vehicles. (In 1996 the number of registered two-wheelers was 23.1 million.) Efficiency improvements of 25 percent are possible for two-stroke engines (two- and three-wheelers). The stringent emission standards proposed for two- and three-wheelers will force manufacturers to switch to four-stroke engines. Efficiency improvements for cars and buses are expected to come primarily from switching from gasoline and diesel to

compressed natural gas (TERI, 1992).

BOX 6.6. MORE ENERGY-EFFICIENT FOUNDRIES IN INDIA

Until recently most of India’s 6,000 small foundries had conventional cupolas (melting furnaces) with low energy efficiencies and high emissions. In 1998 a new divided-blast cupola and pollution control system were commissioned and fine-tuned. Once various control parameters were optimised, the demonstration cupola was far more energy efficient, with coke savings ranging from 33-65 percent relative to average small-scale foundries in India. Emissions of total suspended particulates are below the most stringent emission norm prevailing in India. In addition, the new cupola has a much reduced oxidation loss for silicon and manganese. This success story outlines an appropriate strategy for small-scale foundries to upgrade to an energy-efficient and environmentally cleaner option. This strategy can be adapted not only to other industry clusters in India, but also to units operating under similar conditions in other countries.

Source: TERI, 1998.

The importance of research and development for increasing energy efficiency is still underestimated in India. Spending on research and development increased from 0.35 percent of GNP in 1970 to 0.81 percent in 1994. But this share is still just one-third of the ratio in industrialised countries. Tackling the complex technological problems of the energy sector, particularly end-use efficiencies, will require research and development on a steadily increasing scale.

China

Like India, China is one of the world’s main emerging economies, with a population of more than 1.2 billion.[17] In 1996 China’s primary energy demand was 44,000 petajoules, or 36 gigajoules per capita. Substantial energy efficiency gains could be realised through

intensive investments in the country’s productive sectors.

Industry. In 1995 steel and iron industry consumed 3,740 petajoules, accounting for 13 percent of China’s final energy use with a performance of 46 percent energy efficiency. Energy consumption per tonne of steel will likely drop from 44 gigajoules in 1995 to 35 gigajoules in 2010, which is a little higher than the level in industrialised countries in the 1970s (table 6.10). The potential efficiency savings in some other energy-intensive branches are higher - construction materials could achieve 20 percent and chemicals up to 30 percent, with particular savings in basic chemicals such as ammonia, sulphate, soda, carbide, and olefine production.

Residential. Since the 1980s domestic energy consumption has increased because of higher living standards and expanded living space. Measures such as preventing heat losses, improving electric appliance efficiency, replacing incandescent lamps with fluorescent lamps, improving stoves and boilers, and using cogeneration will enhance energy efficiency in this sector. In 1995 the average efficiency of China’s energy use - as defined by the relationship between useful energy and final energy - was 45 percent in urban areas and 25 percent in rural areas, indicating considerable potential for improvement. By 2010 energy efficiency is expected to reach 50 percent in urban areas and 45 percent in rural areas, close to levels in industrialised countries in the early 1990s (box 6.7). This means savings of 10-15 percent in urban areas and 80 percent in rural areas. These gains are important because the drivers for energy services will be increasing by 5-18 percent a year.

TABLE 6.10. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN CHINA, 2010

Sector and area	Economic potential (percent)	Energy price level assumed	Base year	Reference
Industry				

Iron and steel	15-25	Today's price	1995	Hu, 1997
Cement	10-20	Today's price	1995	Hu, 1997
Foundries	8-14	Today's price	1995	Hu, 1997
Pulp and paper	20-40	Today's price	1995	Hu and Jiang, 1997
Textiles	15-28	Today's price	1995	Hu, 1997
Fertiliser	10-20	Today's price	1995	Hu and Jiang, 1997
Aluminium	20	Today's price	1995	Hu and Jiang, 1997
Brick kilns	32	Today's price	1995	Hu and Jiang, 1997
Refineries	5-10	Today's price	1995	Hu and Jiang, 1997
Ethylene	10-30	Today's price	1995	Hu and Jiang, 1997
Calcium carbide	10-22	Today's price	1995	Hu and Jiang, 1997
Sulphate	14-25	Today's price	1995	CIECC, 1997
Caustic soda	10-30	Today's price	1995	CIECC, 1997
Household				
Lighting	10-40	Today's price	1995	CIECC, 1997
Refrigerator	10-15	Today's price	1995	CIECC, 1997
Air conditioner	15	Today's price	1995	CIECC, 1997
Washing	15	Today's price	1995	CIECC, 1997

Washing machine		Today's price	1995	CIECC, 1997
Cooking utensils	20-40	Today's price	1995	CIECC, 1997
Heating equipment	10-30	Today's price	1995	CIECC, 1997
Agriculture				
Motors	10-30	Today's price	1995	CIECC, 1997
Pump sets	20-50	Today's price	1995	CIECC, 1997
Transportation				
Train (diesel)	5-15	Today's price	1995	Hu, 1997
Train (electric)	8-14	Today's price	1995	Hu, 1997
Cars	10-15	Today's price	1995	Hu, 1997
Vessels	10	Today's price	1995	Hu, 1997

Other sectors. In 1995 other final energy users in the service sector had an average end-use efficiency of about 40 percent. By 2010 technological progress and technical measures are expected to increase the efficiency level by 5-10 percentage points over 1995, reaching the level of industrialised countries in the early 1990s.

Transportation. Transportation is a large and fast-growing energy-consuming sector, especially for petroleum products (2,640 petajoules in 1995, including public transport). By 2010 energy consumption will almost double, with oil products accounting for 87 percent of transport energy consumption. Relative to other sectors, transportation has a low end-use efficiency of around 30 percent. The main technical measures for increasing efficiency are similar to those elsewhere: increase the share of diesel vehicles, rationalise the weight of cars, speed up road construction and improve its quality; increase the share of electric engines and internal combustion engines on trains, and optimise engines.

Better-designed propellers on ships could save 5 percent on ships' fuel consumption. Optimal ship shape energy-saving technology will save 4-10 percent of fuel, and the use of tidal energy another 3-5 percent.

Latin America

Primary energy demand in Latin America grew 2.3 percent a year over the past 20 years, reaching 18,130 petajoules in 1996.[18] The region also contains several emerging economies that are increasing world energy demand. In 1997 Argentina, Brazil, Mexico, and Venezuela used 85 percent of the region's primary energy (EIA, 1999b).

Industry. Four sectors (cement, iron and steel, chemicals, food and beverages) consume 60 percent of industrial energy in Latin America. Iron and steel alone account for 23 percent of industrial energy. Better management of blast furnaces, the injection of gases, and improved processes could reduce energy demand by 10-28 percent (Cavaliero, 1998). Machado and Shaeffer (1998) estimate potential electricity savings of 23 percent in Brazil's iron and steel industry and 11-38 percent in its cement industry (table 6.11). The food and beverage industry and chemical industry have similar efficiency potential (Argentina Secretaria de Energa, 1997; Jannuzzi, 1998).

In Brazil's industrial sector, electrical motors consume 51 percent of electricity, electrochemical processes 21 percent, electrothermal processes 20 percent, refrigeration 6 percent, and lighting 2 percent (Geller and others, 1997 and 1998). In Argentina nearly 75 percent of industrial electricity is used in motors (Dutt and Tanides, 1994) and in Chile it is 85 percent (Valdes-Arrieta, 1993). The Brazilian Electricity Conservation Agency estimates that savings of 8-15 percent are achievable in Brazilian industry based on cost-effective measures such as replacing oversized motors, improving transmission systems, replacing overloaded internal lines and transformers, correcting low power factors, and reducing excessive peak loads (box 6.8). Additional savings of 7-15 percent could be

achieved by using efficient motors and variable speed drives; improving electrical furnaces, boilers, and electrolytic process efficiencies; and disseminating cogeneration in industry (Geller and others, 1998; Soares and Tabosa, 1996). Recycling the heat surplus or installing more efficient equipment could reduce by 10 percent the amount of electricity used in electric ovens. Similar savings for Argentina have been estimated by Dutt and Tanides (1994) and Argentina Secretaria de Energa (1997).

> Low-energy houses need only 10-30 percent of the heat per square metre that is used in the average residential building in West Germany.

The significant potential of combined heat and power is under-exploited in most Latin American countries. The potential is great in sectors such as paper and pulp, chemicals, and the alcohol-sugar industry, because they produce industrial residues that can be used to generate a surplus of electricity, which can then be sold to the common grid. Legislation establishing independent power producers is in place, but there are still problems in regulating buy-back rates, maintenance power, and wheeling between industry and electric utilities.

Residential. Annual energy use for cooking is estimated at 5.2 gigajoules per capita, nearly half of which is from firewood (data cover only Argentina, Brazil, Mexico, and Venezuela). The use of biomass (firewood and charcoal) is declining, however, and the use of liquefied petroleum gas and natural gas is on the rise. Because these fuels are more efficient, per capita energy consumption will be 20 percent lower by 2020. During 1990-95 per capita residential electricity use increased by 4-5 percent a year in Brazil and Mexico. Specific savings in electricity use by appliances range from 20-40 percent over the next 10-20 years for several Latin American countries (see table 6.11).

Commercial and public sectors. More efficient energy use in the commercial and public sectors can be achieved by introducing better boilers and maintenance practices as well as small cogeneration. Mexico is implementing building standards, which will accelerate improvements in energy use (Huang and others, 1998). For lighting, air conditioning, and refrigeration, the main electrical end uses, substantial efficiency improvements are possible for most Latin American countries (see table 6.11).

BOX 6.7. GREEN LIGHT PROGRAMME OF CHINA

China’s Green Light Programme is an energy conservation project supported by UNDP and organised and carried out by the State Economic and Trade Commission of China. The programme is designed to increase the use of lighting systems that are highly efficient, long-lasting, safe, and stable. The goal is to save electricity, reduce environmental pollution from power generation, and improve the quality of working and living. The programme has had several achievements:

- **Electricity savings.** During 1995-2000, 300 million compact fluorescent lamps, thin-tube fluorescent lamps, and other high-efficiency illumination products will save 22 terawatt-hours of electricity (as final energy).
- **Reduced emissions.** By 2000 sulphur dioxide emissions will be reduced by 200,000 tonnes and carbon dioxide emissions by 7.4 million tonnes.

- **Establishing the market.** By creating market-driven demand for high-efficiency lighting products, China will minimise spending for the associated gains. Close attention has been given to upgrading energy-efficient products by improving quality standards and certification.

TABLE 6.11. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN LATIN AMERICA, 2010 AND 2020

Sector and area	**Economic potential (percent)**		**Country/ region**	**Energy price level assumed**	**Base year**	**Source**
	2010	**2020**				
Industry						
Electric motors and drives	15-30[a,d]	30	Mexico	0.06-0.09	1996	Mxico Secretaria de Energa, 1997; Argentina Secretaria de Energa, 1997; EIA, 1999a; Geller and others 1998; IIEC, 1995; Sheinbaum and Rodriguez, 1997
Refrigeration	27-42[b]	15-30[c]	Argentina	(elect)[d]	1997	
Process heat	10-20	21-44	Brazil		1997	
			Chile	0.01-0.02 (fuels)[b]	1994	
Iron and steel		23[b] (elect)	Brazil		1998	Machado and Shaeffer, 1998; Cavaliero 1998; Argentina Secretaria de Energa, 1997; EIA, 1999a; IIEC, 1995
		28[b] (coke)			1994	
		15[a]				
		10[d]	Argentina Chile			
Cement		11-38[b]	Brazil		1998	Machado and Shaeffer, 1998;

		(elect)				Sheinbaum and Ozawa, 1998
Food and beverage		20[b]	Brazil		1998	Jannuzzi, 1998; Argentina Secretaria de Energa, 1997; EIA, 1999a; IIEC, 1995
		30[a]	Argentina		1998	
		6[d] (elect)	Chile		1994	
Residential		**20-40 (elect)**	Mexico,		1996	Mxico Secretaria de Energa, 1997; Argentina Secretaria de Energa, 1997; EIA, 1999a; Machado and Shaeffer, 1998; Friedmann, 1994
			Argentina		1997	
			Brazil		1998	
Cooking		24	Latin America		1997	Author’s estimate
Electrical appliances	20-25	20-40	Mexico		1996	Mxico Secretaria de Energa, 1997; Geller and others 1998
			Brazil		1997	
Lighting	30-80		Brazil	0.03-0.13	1997	Jannuzzi, 1998; Argentina Secretaria de Energa, 1997; EIA, 1999a; Blanc and de Buen, 1994
			Argentina	(fuels and electricity)[b]	1991	
Refrigeration		35-50	Brazil		1998	Machado and Shaeffer, 1998; Mxico

			Argentina Mexico		1996	Secretaria de Energa, 1997
Commercial and public	**20-40 (elect.)**		Mexico		1996	Mxico Secretaria de Energa, 1997;
			Argentina Chile		1997	Argentina Secretaria de Energa, 1997; EIA, 1999a; IIEC, 1995
Shopping centres		13-38 (elect.)	Brazil		1998	Machado and Shaeffer, 1998
Hotels		12-23	Brazil		1998	Machado and Shaeffer, 1998
Lighting	40		Mexico		1996	Mxico Secretaria de Energa, 1997; Jannuzzi and others, 1991; Bandala, 1995
			Brazil		1990	
Public lighting	21-44[a]		Argentina		1991	Argentina Secretaria de Energa, 1997; EIA, 1999a; IIEC, 1995
	37[d]		Chile	0.05[d]		
Transportation	**25**		Argentina		1998	

Note: Data for Argentina refer to the estimated technical potential. Data for Chile are for 2020; for Brazil, 2020 or 2010, as indicated; for Argentina, 2010 or 1998, as indicated; and for Mexico, 2006. a. Argentina. b. Brazil. c. Mexico. d. Chile.

Transportation. About two-thirds of Latin America's transport energy demand is concentrated in Brazil and Mexico, where road transport accounts for 90 percent of the sector's energy consumption. Past improvements in the average specific energy consumption of passenger cars in Mexico (from 491 megajoules per 100 kilometres in 1975 to 423 megajoules in 1990) will likely continue at a similar rate (Sheinbaum, Meyers,

and Sathaye, 1994). Mexico's freight transport has seen efficiency improve from 2.47 megajoules per ton-kilometre in 1975 to 1.8 megajoules per ton-kilometre in 1988. Subway systems have not grown at the same rate as passenger demand for travel in Latin America's major cities, the exception being Curitiba, Brazil. In Argentina the Energy Secretariat estimates that 12 petajoules of fuel can be saved each year in passenger and freight transportation (about 25 percent of the transport sector's energy use in 1995; Argentina Secretaria de Energa, 1998f).

BOX 6.8. EFFORTS TO PROMOTE ENERGY USE BY THE BRAZILIAN ELECTRICITY CONSERVATION AGENCY

In the mid-1980s the Brazilian government established PROCEL, a national electricity conservation agency. The agency is responsible for funding and coordinating energy efficiency projects carried out by state and local utilities, state agencies, private companies, universities, and research institutes. It is also responsible for evaluating efficiency programs carried out by privatised utilities. PROCEL also helps utilities obtain low-interest financing for major energy efficiency projects. In 1998 PROCEL's core budget for grants, staff, and consultants was about $20 million, with about $140 million a year going towards project financing.

PROCEL estimates that its activities saved 5.3 terawatt-hours of electricity in 1998, equivalent to 1.8 percent of Brazil's electricity use. In addition, PROCEL took credit for 1.4 terawatt-hours of additional power production due to power plant improvements that year. The electricity savings and additional generation enabled utilities to avoid constructing about 1,560 megawatts of new capacity, meaning approximately $3.1 billion of avoided investments in new power plants and transmission and distribution facilities. The overall benefit-cost ratio for the utility sector was 12:1. About 33 percent of the savings in 1998 came from efficiency improvements in refrigerators, freezers, and air conditioners, 31 percent from more efficient lighting, 13 percent from installation of meters, 11 percent from motor projects, 8 percent from industrial programs, and 4 percent from other activities (Geller and others, 1998).

Africa

Africa has great potential for energy efficiency savings in industry, households, and transportation, which together account for more than 80 percent of the continent’s energy consumption (21 gigajoules per capita in 1996).[19] When assessing the economic efficiency potentials in table 6.12, however, one has to keep in mind the enormous differences in development in Africa and the fact that the literature on this subject is scarce and often dated. South Africa and most North African countries are at more advanced stages of industrialisation and motorisation than the rest of the continent.

TABLE 6.12. ECONOMIC ENERGY EFFICIENCY POTENTIALS IN AFRICA, 2020

Sector and area	Economic potential (percent)	Country	Energy price level assumed	Base year	Source
Industry					
Total industry	15	Zimbabwe		1990	TAU, 1991
	about30	Zambia		1995	SADC, 1996
	32	Ghana		1991	Davidson and Karekezi, 1991; Adegbulugbe, 1992a
	25	Nigeria		1985	Davidson and Karekezi, 1991; SADC, 1997
	>20	Sierra Leone		1991	Adegbulugbe, 1993
	20	Mozambique			

	20	Mozambique			
Iron and steel	7.2	Kenya			Nyoike, 1993
Cement	11.3	Kenya			Nyoike, 1993
	15.4	Ghana		1988	Opam, 1992
	9.8	Kenya			Nyoike, 1993
Aluminium (sec.)	44.8	Kenya			Nyoike, 1993
Refineries	6.3	Kenya			Nyoike, 1993
Inorganic chemicals	19.0	Kenya			Nyoike, 1993
Consumer goods	25	Kenya			Nyoike, 1993
Food	16-24	Mozambique		1993	SADC, 1997
	1-30	Ghana		1988	Opam, 1992
Cogeneration	600 MW	Egypt		1998	Alnakeeb, 1998
Residential					
Electric appliances	20-25	Mozambique	1993	1991	SADC, 1997
	11	South Africa		1995	*Energy Efficiency News,* 1996
Commercial/public/agriculture					
Electricity	20-25	Mozambique	1993	1995	SADC, 1997
	up to 50	Egypt	1998	1998	Alnakeeb and others, 1998
Agriculture/ forestry	12.5	Tanzania (biopower)	1993	1993	
Transportation					
Cars, road system	30	Nigeria		1985	Adegbulugbe,

					1992a
Total transport	30	Ethiopia		1995	Mengistu, 1995

BOX 6.9. ENERGY-EFFICIENT COOKING IN RURAL AFRICA

The Kenya Ceramic Jiko initiative is one of the most successful urban cookstove projects in Africa. The initiative promotes a charcoal-based cookstove with an energy efficiency of about 30 percent. The stove is made of local ceramic and metal components. Since the mid-1980s more than 500,000 of the stoves have been produced and distributed in Kenya. The stove is not a radical departure from the traditional all-metal stove. Rather, it is an incremental development. On the other hand, the stove requires that charcoal be produced and transported.

The improved stove is fabricated and distributed by the same people who manufacture and sell traditional stoves. From the beginning the stove initiative received no subsidies - a decision that had a tremendous impact on its development, encouraging private entrepreneurs to invest their capital and work hard to recover their investment. This drive to recover the original investment helped ensure self-sustained production, marketing, and commercialisation of the charcoal stoves. In addition, the lack of subsidy enhanced competition between producers, bringing down its market price to a more realistic and affordable level for Kenya’s low-income urban households. The stove design has been successfully replicated in Malawi, Rwanda, Senegal, Sudan, Tanzania, and Uganda.

Industry. Studies indicate that good housekeeping measures can save substantial amounts of energy in African industries (see table 6.12). Potential energy savings in national industries range from 15-32 percent by 2020. Results from energy audits in Nigeria (of two cement plants, one steel plant, and a furniture manufacturing plant) show potential savings of up to 25 percent. In 28 small- and medium-size industries in Zambia and Zimbabwe the potential savings are between 15 and 30 percent, in Kenyan industries about 25 percent, in nine industrial plants in Egypt about 23 percent, in Ghana 32 percent, and in Sierra Leone more than 20 percent. A more recent analysis carried out in industries

in Mozambique indicates an economic electricity saving potential of 20 percent (SADC, 1997). Cogeneration also seems to have unexploited potential - in Egypt four industrial branches could save 600 megawatts by engaging in cogeneration (Alnakeeb, 1998).

Residential. The use of inefficient traditional three-stone fuelwood stoves for cooking, mainly in rural areas, results in considerable energy losses. The end-use efficiency of the stoves ranges from 12-18 percent. Promoting better biomass-cooking stoves and switching to modern fuels would greatly reduce the huge energy losses in this sector. Better cooking stoves could raise efficiency to 30-42 percent in Ghana, Kenya, and Uganda (box 6.9). In urban areas the focus should be on energy-efficient appliances, lighting, and other housekeeping measures for domestic appliances. In lighting a shift from kerosene to incandescent lamps, and from incandescent lamps to fluorescent and compact fluorescent lamps, would increase energy efficiency (see table 6.12).

Transportation. Road transport is the dominant mode in Africa. Nearly all vehicles are imported from overseas, often used cars and trucks. Potential savings are achievable by using roadworthy vehicles and changing policies. Vehicles tend to have low fuel efficiency. The average fuel efficiency in Nigeria is estimated to be about 18 litres of gasoline per 100 kilometres (Adegbulugbe, 1992a). Fuel efficiency is low because the vehicle fleet is old and poorly maintained, because of traffic congestion in most urban centres, and because of bad driving habits. Energy savings of 30 percent could be achieved in the road subsector by shifting from an energy-intensive transport mode to a less energy-intensive public transport system and by adopting traffic management schemes. In Ethiopia and Nigeria the demand for gasoline and diesel could be cut by 30 percent by emphasising public transportation over private automobiles (Adegbulugbe, 1992b; Mengistu, 1995).

The economic potential of energy efficiency - a systemic perspective

The preceding section covered only individual technology for energy conversion and

use.[20] But additional - and sometimes major - energy savings can be realised by looking at energy-using systems in a broader sense. Aspects of this systemic view include:

- **Optimising the transport and distribution of energy. Commercial energy use is often highly decentralised, yet the energy is produced in central plants; examples include electricity and district heating networks.**

- **Optimising the location of energy users to avoid transporting goods or people.**

- **Optimising according the second law of thermodynamics by supplying the suitable form of energy, including heat at the needed temperature and pressure, or by exploiting opportunities for energy cascading.**

These concepts are not new. But they are often neglected in the planning of cities and suburbs, industrial sites and areas, airports, power plants, and greenhouses.

Excellent examples of the systemic approach include not only technical systems but also innovations in joint planning and coordinated - or even joint - operation or financing of energy generating, distributing, or using systems (IEA, 1997a):

- **A district heating system in Kryukovo, Russia, that supplies almost 10 petajoules of heat was to a large extent manually controlled and monitored. Automated control of substations, remote sensing, and control between substations and the operator working station resulted in savings of 20-25 percent.**

- **Organising urban mobility is a major challenge for all countries. In areas with rapidly growing populations, planning decisions on residential, industrial, and commercial areas do not adequately consider induced mobility demand and possible modes of transportation. Incentives for car sharing, park-and-ride systems, and parking influence the use of cars and public transportation. In**

developing countries a lack of capital for subways must not lead to disastrous traffic jams. A possible solution has been realised by the bus system in Curitiba, Brazil (IEA, 1997a, p. 103).

- **The adequate use of the exergy of energy carriers is another systemic aspect of energy efficiency. Cogeneration takes many forms: combined gas and steam turbines, gas turbines instead of burners, engine-driven cogeneration, and fuel cells that can supply heat at the correct levels of temperature and pressure (Kashiwagi, 1999). Excess heat at low temperatures may be used in heat transformers, heat pumps, or adsorption cooling systems. Production processes with high-temperature heat demand can be located in industrial parks surrounded by production processes with lower-temperature heat that can be reused in greenhouses or fish ponds (Kashiwagi, 1995).**

These systemic aspects have been investigated less intensively because such systems demand a lot of coordinated planning and action by several actors and institutions. They often also demand changes in legal frameworks and decision-making in companies and administrations. Additional risks have to be managed by new entrepreneurial solutions and insurance services. In many cases, however, the efficiency potentials if such systems may exceed the economic efficiency potentials of individual technologies.

Technical and theoretical potentials for rational energy use after 2020

Many energy economists expect energy demand to increase in industrialised countries, accompanied by a substantial shift to natural gas, nuclear power, and renewables to avoid climate changes caused by energy-related greenhouse gases (chapter 9).[21] Explicitly or implicitly, those expectations assume that substantial cost-effective efficiency improvements will be exhausted within the next 20 years, contributing to new growth in energy demand after some 25 years of stagnation. But applied scientists and engineers

have questioned the judgement that feasible improvements in energy efficiency are limited to 30-40 percent (Jochem, 1991; De Beer, 1998; ETSU, 1994; Blok and others, 1996; Kashiwagi and others, 1998). These authors argue that, depending on new technology and scientific knowledge, the long-term technical potential for rational energy use may even exceed 80 percent in the 21st century, driven by efforts to:

- ***Increase exergy efficiency*** **(which today is less than 15 percent, even in industrialised countries) by exploiting the different temperatures of heat streams and using the adequate form of final energy or heat at the needed temperature level.**

- ***Decrease the level of useful energy*** **by reducing losses (for example, through insulation or heat recovery) and by substituting energy-intensive processes (such as membrane and absorption technologies instead of thermal separation, thin slab casting of steel instead of rolling steel sheets, new catalysts or enzymes, new bio-technical processes, and inductive electric processes instead of thermal surface treatment).**

- ***Apply new materials*** **(new compound plastics, foamed metals, nano-technology applications).**

- ***Intensify recycling of energy-intensive materials*** **(increased shares of recycled plastics, aluminium, or flat glass, which still have low recycling rates in most regions).**

- ***Re-substitute wood, natural fibres, and natural raw materials for energy-intensive plastics*** **(due to great potential for genetic manipulation of plants and substitution among energy-intensive materials; see box 6.1).**

Catalysts, enzymes,

new materials, and new processes will make possible the substitution of many energy-intensive processes.

Because of the unbalanced perception between the long-term potential for rational energy use and energy conversion and supply technologies (Jochem, 1991), the huge long-term potential for increasing energy efficiency at the end-use level will likely remain underestimated for some time. Indeed, given the enormous economies of scale in fast-growing national, regional, and global markets, the economic efficiency potentials cited above for 2010 and 2020 may be too small in many cases.

To use as many energy sources as possible, the concept of cascaded energy use must be introduced in the energy conversion and end-use sectors. Cascaded energy use involves fully harnessing the heat produced by fossil fuel combustion (from its initial 1,700°C down to near-ambient temperatures), with a thermal 'down flow' of heat analogous to the downward flow of water in a cascade (Kashiwagi, 1995; Shimazaki and others, 1997). Applications that exploit the full exergetic potential of energy in multiple stages (cascaded) are not common. To exploit the exergetic potential of industrial waste heat, energy transfers between the industrial and residential or commercial sectors are advisable. But low energy prices make it difficult to find economically attractive projects.

For refrigeration, air conditioning, and hot water supply, it is possible to meet most of the heat demand with low-exergy waste heat obtained as a by-product of high-temperature, high-grade primary energy use in heat engines or fuel cells, in a cascaded use of cogeneration. From a thermodynamic viewpoint it is appropriate to combine low-exergy heat sources, such as solar and waste heat, with systems requiring low-exergy heat, such as heating, cooling, and air conditioning.

The level of specific useful energy demand can be influenced by innumerable technological changes without reducing the energy services provided by energy use and without impairing comfort. A few examples demonstrate these almost unconverted possibilities:

- **The quality of insulation and air-tightness determine the demand for useful energy in buildings, furnaces, refrigerators and freezers.**

- **Low-energy houses need only 10-30 percent of the heat per square metre that is used in the average residential building in West Germany (box 6.12). A cold-storage depot or a refrigerator could be operated by outdoor air in the winter in zones with moderate climate. A substantial part of industrial waste heat occurs at temperatures below 50^{o}C. Water adsorption chillers provide a way to recover such heat sources and produce cooling energy (Saha and Kashiwagi, 1997), increasing energy efficiency.**

- **Catalysts, enzymes, new materials, and new processes will make possible the substitution of many energy-intensive processes. High energy demand to activate chemical reactions, with high-pressure and high-temperature processes, may be rendered unnecessary by new catalysts or biotechnological processes. Membrane processes will use only a small percentage of the useful energy needed today in thermal separation processes. The production of iron - which today involves energy-intensive sintering and coke-making - will be switched to the new coal metallurgy, with substantial energy savings. Over the long term, the energy-intensive rolling-mill operation of steel-making will be replaced by continuous thin slab casting or even spraying of steel sheets.**

- **New materials for cutting edges will improve surface quality, avoiding several machine operations. Lasers will reduce the specific energy demand of metal cutting, and inductive electric processes will save energy in thermal surface**

treatment. New compound plastics or foamed metals will induce less energy demand in manufacturing and (because of smaller specific weight and reduced losses due to inertia) be used in vehicles and moving parts of machines and engines.

Over the past century energy systems in industrialised countries saw efficiency increase by 1.0-1.5 percent a year. Looking at the theoretical and technical potential of future energy efficiency, a similar increase of 1.0-1.5 percent a year appears possible over the next century. Increases in efficiency will be steadily exhausted by implementing economic efficiency opportunities and steadily fed by implementing technical innovations and cost reductions for energy-efficient technology. This process can be understood as a constant economic efficiency potential of 25-30 percent over the next 20 years, similar to the observation at the energy supply side that the ratio of proven reserves to consumption of oil remains at 30-40 years due to continuous searching for new reserves and technical progress on prospecting, drilling, and production techniques.

Obstacles, market imperfections, and disincentives for efficient energy use

Energy efficiency improvements since the oil shock of 1973 may have done more to redesign energy markets than did changes in conventional energy supply systems.[22] And as noted, such improvements still offer huge opportunities and can contribute to sustainable development in all regions. But given today's levels of energy-related knowledge, decision-making, and power structures, there is much evidence that the great potential for rational energy use will be overlooked by many companies, administrations, and households or deemed purely theoretical or unfeasible.

Of course, it will not be easy to fully achieve economic efficiency potentials, the 'fifth energy resource'. The technologies are decentralised and technologically very different, and increased efficiency is harder to measure than energy consumption. In addition,

instead of a dozen large energy supply companies or a few engineering companies in a country, millions of energy consumers have to decide on their energy efficiency investments and organisational measures. The heterogeneity and diversity of energy consumers and manufacturers of energy-efficient equipment contribute to a low perception of the high potential of energy efficiency. Because of this variety and complexity, energy efficiency is not appealing for the media or for politicians (Jochem, 1991).

In theory, given all the benefits of energy efficiency at the micro-economic and macroeconomic levels, a perfect market would invest in, and allocate the rewards from, new energy-efficient technologies and strategies. But in practice, many obstacles and market imperfections prevent profitable energy efficiency from being fully realised (Jochem and Gruber, 1990; Hirst, 1991; IEA, 1997a; Gardner and Stern, 1996; Reddy, 1991). Although these obstacles and market imperfections are universal in principle, their importance differs among sectors, institutions, and regions.

General obstacles

Obstacles to end-use efficiency vary by country for many reasons, including technical education and training, entrepreneurial and household traditions, the availability of capital, and existing legislation. Market imperfections include the external costs of energy use (Hohmeyer, Ottinger, and Rennings, 1997) as well as subsidies, traditional legislation and rules, and traditions, motivations, and decision-making in households, companies, and administrations. Finally, an inherent obstacle is the fact that most energy efficiency investments remain invisible and do not contribute to politicians’ public image. The invisibility of energy efficiency measures (in contrast to photovoltaic or solar thermal collectors) and the difficulty of demonstrating and quantifying their impacts are also important. Aspects of social prestige influence the decisions on efficiency of private households - as when buying large cars (Sanstad and Howarth, 1994; Jochem, Sathaye,

and Bouille, 2000).

OECD countries. Obstacles to and market imperfections for energy efficiency in end-use sectors have been observed in OECD countries for more than 20 years.[23] While limited, empirical research on the barriers underscores the diversity of individual investors (with thousands of firms, hundreds of thousands of landlords, and millions of consumers in a single country).

***Lack of knowledge, know-how, and technical skills and high transaction costs.* Improved energy efficiency is brought about by new technology, organisational changes, and minor changes in a known product, process, or vehicle. This implies that investors and energy users are able to get to know and understand the perceived benefits of the technical efficiency improvement as well as evaluate possible risks. It also implies that investors and users have to be prepared to realise the improvement and to take time to absorb the new information and evaluate the innovation (OTA, 1993; Levine and others, 1995; Sioshansi, 1991). But most households and private car drivers, small and medium-size companies, and small public administrations do not have enough knowledge, technical skills, and market information about possibilities for energy savings. The construction industry and many medium-size investment firms face the same problem as small companies on the user's side. Managers, preoccupied with routine business, can only engage themselves in the most immediately important tasks (Velthuijsen, 1995; Ramesohl, 1999). Because energy efficiency reduces a small share of the energy costs of total production or household costs, it gets placed on the back burner.**

***Lack of access to capital and historically or socially formed investment patterns.* The same energy consumers, even if they gain knowledge, often have trouble raising funds for energy efficiency investments. Their capital may be limited, and addi-tional credit may be expensive. Especially when interest rates are high, households and small firms tend to prefer to accept higher current costs and the risk of rising energy prices instead of taking**

a postponed energy credit (DeCanio, 1993; Gruber and Brand, 1991).

***Disparity of profitability expectations of energy supply and demand.* The lack of knowledge about energy efficiency among small energy consumers raises their perceptions of risk, so energy consumers and suppliers expect different rates of return on investments (Hassett and Metcalf, 1993). Energy supply companies in countries with monopolistic energy market structures are willing to accept nominal internal rates of return of 8-15 percent (after tax) for major supply projects (IEA, 1987). But for efficiency investments, energy consumers demand - explicitly or without calculating - payback periods between one and five years, which are equivalent to a nominal internal rate of return of 15-50 percent (DeCanio, 1993; Gruber and Brand, 1991). This disparity in rate of return expectations also seems to apply to international loans, putting energy efficiency investments in developing countries at a disadvantage (Levine and others, 1995).**

***The impact of grid-based price structures on efficient energy use.* Grid-based forms of energy play a dominant role in OECD countries. The structure of gas, electricity, and district heat tariffs for small consumers and the level of the load-independent energy charge are important for energy conservation. Tariff structures are designed in two parts to reflect two services - the potential to obtain a certain amount of capacity at any given time, and the delivered energy. The capacity charge plays an important role in profitability calculations for investments where efficiency improvements do not reduce capacity demand, such as inverters on electric engines or control techniques in gas or district heating (IEA, 1991). In addition, in most OECD countries utilities still do not offer time-of-use or seasonal rates to small consumers, which would reward them for using energy during off-peak hours. This, however, may change in fully liberalised electricity and gas markets.**

***Legal and administrative obstacles.* There are legal and administrative obstacles in almost all end-use sectors. They are mostly country specific, and often date back to before 1973,**

when energy prices were low and declining in real terms and there was no threat of global warming. For most local government authorities the budgeting format is an 'annual budgeting fixation', which means that they cannot transfer funds from the recurrent to the investment budget. With a lot of other urgent needs calling for capital investment, energy efficiency measures are given low priority. The poor perception of public goods adds to the obstacles confronting energy efficiency in developing and transition economies (see below).

Other market barriers. **The investor-user dilemma points to the fact that for rented dwellings or leased buildings, machines, or vehicles, there are few incentives for renters to invest in property that they do not own. Similarly, landlords, builders, and owners have few incentives to invest because of the uncertainty of recovering their investment through higher rent (Fisher and Rothkopf, 1989; Golove, 1994). Finally, the quality of delivered energy (as with unstable frequencies or voltages of electricity or impurities in gasoline or diesel) may pose a severe barrier for effi-ciency investments (electronic control or high efficiency motors).**

> Because energy efficiency reduces a small share of the energy costs of total production or household costs, it gets placed on the back burner.

Additional barriers in transition economies.[24] Transition economies did not experience the sharp increase in world energy prices in the 1970s. As a result opportunities for more efficient energy use were scarcely realised in these countries. Most transition economies suffer from all the barriers described above for OECD countries, as well as from additional market problems stemming from the legacy of central planning. The deep economic and

structural crisis during the early years of transition shifted the investment priorities of industrial and commercial companies to short-term decisions, helping them to survive. Technological innovations that increase energy efficiency are hardly considered a priority in many transition economies (Borisova and others, 1997). There are, however, substantial differences among most Eastern European countries and members of the Commonwealth of Independent States.

Unpaid energy bills. **The economic crisis in transition economies created special obstacles to investing in energy efficiency, including non-payments and non-monetary payments (barter, promissory notes, and other surrogates by energy consumers, mutual debt clearing between companies). In Georgia less than 30 percent of residential electricity rates were paid in 1994; industrial payments fell to 16 percent, and 25-50 percent of the electricity supply was not accounted or billed (World Bank, 1996; TACIS, 1996). In Russia about 25 percent of generated electricity was not paid for by customers in 1995-97 (BEA, 1998). Industrial and commercial customers covered up to 80 percent of their energy bills using non-monetary and surrogate means (Russian Federation Ministry of Fuel and Energy, 1998). The use of barter is contributing to the neglect of potential reductions in energy costs through efficiency measures. Experience in Eastern Europe, however, demonstrates that cutting customers off from the electricity or gas supply persuades them to pay (box 6.10).**

BOX 6.10. THE IMPLICATIONS OF TERMINATING ELECTRICITY SUBSIDIES IN HUNGARY

Raising energy prices to cost-covering levels can produce miracles. Until 1997 Hungary spent $5-10 million a year on energy efficiency improvements. In January 1997 energy prices were raised to market-based levels - and in just two years, investments in energy efficiency jumped to $80 million a year. The usual argument against correct energy pricing, that consumers cannot pay the bills, is not proven in Hungary. Just 10 percent of the national energy bill remained unpaid, and that just partly. True, retirees with low incomes have difficulties. But they are not the big consumers with high bills. The problem is a social problem, and has been solved by special payment schemes in the social policy framework of local and national budgets.

Barriers to energy metering. **Many energy customers in transition economies are still not equipped with meters and controllers or have simplistic, outdated meters. In particular, residential customers in the Commonwealth of Independent States often have no meters to measure the use of natural gas, heat, and hot water, reflecting a long-held view that heat and fuel are public goods. According to the Russian Federation Ministry of Fuel and Energy (1998), only about 10 percent of heat customers (and no more than 15 percent of hot water and natural gas customers) are equipped with meters. Since 1994, however, significant efforts have been made to manufacture modern meters and controllers and to develop related services (certification, maintenance, and verification) (Minfopenergo, 1996). Meters are far more common in Eastern Europe, because since the 1980s these countries have had to import needed energies in exchange for hard currency.**

Lack of cost-based tariffs for grid-based energies. **Natural gas, electricity, heat, and hot water are supplied to users in the Commonwealth of Independent States and some Eastern European countries by regional or local energy monopolies with government participation and municipal distribution companies. Energy tariffs are still set by federal and regional energy commissions in most of the Commonwealth of Independent States. In Russia a large portion of customers are subsidised; fuels are of poor quality, expensive, or both; resellers charge excessive costs and receive large profits; detailed information is lacking on the production costs of suppliers; and the decisions of regional commissions do not sufficiently reflect cost considerations, but depend on the political priorities of the local authorities (Vasiliev and others, 1998).**

Subsidies. **In all Commonwealth of Independent States countries and a few Eastern European countries the grid-based energy supply of residential and agricultural customers is still subsidised. Subsidies are driven by traditional concepts of public goods or social**

policy. In addition, some groups (war veterans, low income families) pay discounted residential tariffs. In Ukraine the government paid 20 percent of the cost of natural gas for residential customers in 1996 (Gnedoy, 1998). Russian municipalities spend 25-45 percent of their budgets on residential heat subsidies, covering more than half of heat bills (Bashmakov, 1997a).

Subsidised energy prices reduce the economic attractiveness of energy efficiency measures. Cross-subsidies for electric power in the Commonwealth of Independent States distort price signals between groups of customers. For instance, cross-subsidies for residential electricity account for 20-60 percent of prices for industrial customers in different regions of Russia (Moloduik, 1997; Kretinina, Nekrasov, and Voronina, 1998). In principle, this price structure would lead to large investments in efficiency in Russian industry. But non-payment of energy bills prevents that from happening. The case for abolishing electricity subsidies in most Eastern European countries demonstrates that the social aspects of such a pricing policy can be addressed by social policy at the municipality level (see box 6.10).

> Subsidised energy prices reduce the economic attractiveness of energy efficiency measures.

Additional barriers in developing countries. The general obstacles to efficient energy use are sometimes more intense in developing countries than in OECD or transition economies.[25] But there are similarities between subsidies and pricing policies in developing and transition economies. The situation in developing countries may be more complex given the big differences in energy use, income, development, and infrastructure between urban and rural areas in India, China, Latin America, and Africa.

Lack of awareness of potential benefits. **The limited awareness of the potential for energy efficiency is the most important obstacle to wide-scale adoption of energy efficiency measures and technologies in developing countries. Limited awareness is a by-product of inadequate information infrastructure to raise awareness of the potential for energy efficiency and of available technologies and proven practices. The media used to raise awareness in most developing countries limit the audience. Awareness campaigns rely on radio, television, and newspapers, which most rural populations - the majority of the population in developing countries - do not have access to. In addition, managers in industry do not have timely information on available efficiency technology (Reddy, 1991), and many producers of end-use equipment are unacquainted with energy-efficient technology and related knowledge.**

Many developing countries still lack an effective energy efficiency policy at the national level. **Energy supply policies are preferred in most developing countries because of the focus on development policies. This pattern may also be due to the fact that grid-based energy supplies are often owned by national or local governments, a pattern that supports rigid hierarchical structures and closed networks of decision-makers.**

Energy supply constraints. **In some developing countries, energy supply constraints provide no alternative fuel and technology options for consumers. The limited availability of commercial fuels (petroleum products, electricity) in rural areas impedes switching to more energy-efficient stoves, dryers, and other technologies, posing a major challenge for energy policy (see chapter 10).**

Inappropriate energy pricing and cross-subsidies. **Energy prices are still below marginal opportunity costs in many developing countries, reflecting the desire of governments to use energy supply to achieve political objectives. Successive governments have upheld energy subsidies over decades, making it politically difficult to raise energy prices to the level of marginal opportunity costs (box 6.11; Nadel, Kothari, and Gopinath, 1991).**

Lack of trained staff, operators, and maintenance workers. **Insufficient energy workers are an important constraint to the investment and operation of buildings, machines, plants, and transport systems (Suzuki, Ueta, and Mori, 1996).**

Lack of capital and import of inefficient used plants and vehicles. **Many energy efficiency measures are delayed by a lack of financing. The availability of credit at high interest rates tends to make energy efficiency investments a low priority. In many developing countries there is also a conflict among investment priorities. Growing economies generally favour investments in additional capacity over investments in energy efficiency. This tendency and lack of capital lead to imports of used plants, machinery, and vehicles, aggravating the problem (see the section on technology transfer, above).**

Proliferation of inefficient equipment and the desire to minimise initial costs. **In the absence of energy labelling schemes and of standards for energy efficiency, energy-inefficient products continue to be manufactured and marketed. Examples include diesel-fuelled irrigation pumps, motors, and transformers. Many users focus on minimising initial costs, with little regard for operating efficiency and life-cycle costs. Thus they tend to opt for cheaper, locally manufactured, inefficient equipment.**

Target group-specific and technology-specific obstacles

Many target group-specific and technology-specific obstacles also impede investments in energy efficiency.[26]

Buildings. Lack of information and knowledge is a problem not only among building owners, tenants, and users in *industrialised countries,* but also among architects, consulting engineers, and installers (IEA, 1997a; Enqute Commission, 1991). These groups have a remarkable influence on the investment decisions of builders, small and medium-size companies, and public authorities. The separation of spending and benefits

(or the landlord-tenant dilemma) is common in rented buildings because the owner of a building is not the same as the user (IEA, 1991). This obstacle impedes the adoption of efficient space heating, air conditioning, ventilation, cooling, and lighting equipment in leased buildings and appliances. It is also a problem in the public sector, where schools, sports halls, hospitals, and leased office buildings may have a variety of owners - or where local governments operate and use buildings owned by state or federal governments. Building managers are often not sufficiently trained and do not receive adequate incentives for excellent performance. Planners and architects are often reimbursed based on the total investment cost, not the projected life-cycle cost of the planned building or equipment.

BOX 6.11. DISTORTED ENERGY PRICES RESULT IN BIG LOSSES FOR INDIAN SUPPLIERS

Distorted energy prices are a major obstacle to energy efficiency. In India electricity tariffs vary considerably between states and types of users. The average cost of supply for the country’s electricity boards is $0.049 a kilowatt-hour - yet revenue collection averages just $0.037 a kilowatt-hour. Utility losses are mounting and were reported to be $1.49 billion in 1994/95 (GOI, 1995). High commercial losses are mainly caused by the irrational tariff structure, which provides large subsidies to agricultural and domestic uses (see table).

Electricity tariffs in Indian states, 1998 (U.S. cents per kilowatt-hour)

State electricity board	User						
	Domestic	Commercial	Agriculture/ irrigation	Industry	Rail transport	Exports to other states	Average
Haryana	4.7	7.5	1.2	7.5	7.5	3.2	5.3
Himachal	1.6	4	1.4	3.5	n.a.	3.5	2.8

Pradesh							
Jammu, Kashmir	0.7	1.2	0.2	0.9	n.a.	n.a.	0.8
Kerala	1.4	4.6	0.5	2.4	n.a.	n.a.	2.2
Madhya, Pradesh	1.7	7.3	0.1	7.4	11.8	2.1	5.1
West Bengal	1.9	4.7	0.6	5.9	6.7	n.a.	3.3
Average	**2.9**	**6.7**	**0.5**	**6.9**	**8.5**	**2.9**	**4.1**

n.a. Not available.
Source: Ministry of Power, Government of India (http://powermin.nic.in/plc72.htm).

In many *developing countries* building design has been imitated from industrialised countries regardless of different climates, domestic construction materials, and construction traditions. This approach often results in an extremely energy-consuming design for cooling equipment in office buildings in warm developing countries. Houses in higher-income developing countries are often built by the affluent with a view to projecting prestige rather than reflecting economic concerns. Such buildings are generally devoid of energy efficiency aspects. Lack of information on energy-efficient architecture also undermines energy-efficient building standards and regulations. And in countries where such standards and regulations exist, non-compliance is a constraint.

Household appliances and office automation. Residential consumers in *industrialised countries* substantially underinvest in energy-efficient appliances or require returns of 20 to more than 50 percent to make such investments (Sioshansi, 1991; Lovins and Hennicke, 1999). Related obstacles include a lack of life-cycle costing in a culture of convenience, longstanding ties to certain manufacturers, aspects of prestige, and the investor-user

dilemma in the case of rented apartments or office equipment.

Low incomes make it difficult for households in *developing countries* to switch from lower efficiency to higher efficiency (but more expensive) devices (improved biomass cook stoves, and liquefied petroleum gas and kerosene stoves). Similarly, fluorescent and compact fluorescent lamps are often not bought due to the lack of life-cycle costing by households.

Small and medium-size companies and public administration. In most small and medium-sized companies, all investments except infrastructure are decided according to payback periods instead of internal interest rate calculations. If the lifespan of energy-saving investments (such as a new condensing boiler or a heat exchanger) is longer than that of existing production plants and machinery and if the payback period is expected to be even for both investments, entrepreneurs expect (consciously or unconsciously) higher profits from energy-saving investments (table 6.13).

Lack of funds is a severe constraint for small and medium-size local governments in many countries. Many communities with high unemployment are highly indebted. Making matters worse, municipalities often receive a significant share of their annual budgets through some kind of tax or surcharge on electricity, gas, or district heat sales to their residents, lowering the enthusiasm of local politicians for promoting energy conservation. Finally, in public budget planning, budgets for operating costs are often separate from budgets for investment. Thus possible savings in the operating budget from energy efficiency investments are often not adequately considered in the investment budget.

For small and medium-sized enterprises and communities, installing new energy-efficient equipment is far more difficult than simply paying for energy (Reddy, 1991). Many firms (especially with the current shift towards lean firms) suffer from a shortage of trained technical staff (OTA, 1993) because most personnel are busy maintaining production. In

the Netherlands a lack of available personnel was considered a barrier to investing in energy-efficient equipment by one-third of surveyed firms (Velthuijsen, 1995).

Insufficient maintenance of energy-converting systems and related control equipment causes substantial energy losses. Outsiders (external consultants, utilities) are not always welcome, especially if proprietary processes are involved (OTA, 1993). Many companies cannot evaluate the risks connected with new equipment or control techniques in terms of their possible effects on product quality, process reliability, maintenance needs, or performance (OTA, 1993). Thus firms are less likely to invest in new, commercially unproven technology. An aversion to perceived risks is an especially powerful barrier in small and medium-size enterprises (Yakowitz and Hanmer, 1993).

In *transition economies* small companies and local authorities may not be able to afford an energy manager.

In *developing countries* lack of information and technical skills is an enormous problem for small and medium-sized firms, because such firms often account for a large portion of the economy. In addition, the possible disruption of production is perceived as a barrier to investments in energy efficiency. Although such an investment may be economically attractive, unexpected changes in production increase the risk that the investment will not be fully depreciated.

TABLE 6.13 PAYBACK CALCULATIONS AS A RISK INDICATOR LEAD TO UNDER-INVESTMENT IN PROFITABLE, LONG-LASTING ENERGY EFFICIENCY INVESTMENTS

		Useful life of plant (years)							
		3	**4**	**5**	**6**	**7**	**10**	**12**	**15**
Payback	**2**	24%	35%	41%	45%	47%	49%	49.5%	50%

time	**3**	0%	13%	20%	25%	27%	31%	32%	33%
requirement	**4**		0%	8%	13%	17%	22%	23%	24%
(years)	**5**			0%	6%	10%	16%	17%	18.5%
	6				0%	4%	10.5%	12.5%	14.5%
	8	**Unprofitable**					4.5%	7%	9%

> **Note: Percentages are annual internal rates of return. Continuous energy saving is assumed over the entire useful life of the plant. Profitable investment possibilities are eliminated by a four-year payback time requirement.**

Large enterprises and public administrations. Mechanisms are often lacking to acknowledge energy savings by local administrations, public or private. Public procurement is generally not carried out on the basis of life-cycle cost analysis. Instead, the cheapest bidder gets the contract - and as long as the offered investment meets the project’s specifications for energy use, it need not be energy efficient. The industrial sector, where managers are motivated to minimise costs, poses the fewest barriers to energy-efficient investment (Golove, 1994). But DeCanio (1993) shows that firms typically establish internal hurdle rates for energy efficiency investments that are higher than the cost of capital to the firm. This fact reflects the low priority that top managers place on increasing profits by raising energy productivity.

Developing countries **often lack sufficient human resources to implement energy efficiency projects and to adequately operate and service them. Thus, even when firms recognise the potential of energy efficiency and want to harness the benefits of energy efficiency measures, they are often hampered by a dearth of skilled staff and consultants and by a lack of competent energy service companies. Capital constrains also impede rational energy use in these countries. Furthermore, low capacity use (sometimes as low as 30 percent; World Bank, 1989) affects efficient energy use by industry. Low capacity use is**

caused by many factors, including poor maintenance, lack of spare parts and raw materials, and unsuitable scale and design of plants.

These factors are often complicated by the risk-averse management of big firms. This attitude usually stems from resistance to change, limited knowledge on the technical and economic analysis of energy efficiency technology, and a paucity of data on the experiences of previous users of such measures or technology.

Transportation. The transport policies of most countries rarely view transportation as an energy issue. Rather, transportation is considered a driver of economic growth with the development of infrastructure for moving goods and people. This policy is strongly supported by associations of car drivers, the road transport and aviation industries, and vehicle manufacturers. Most countries have no fuel efficiency standards for new vehicles; the exceptions are for cars as in Canada, Japan, and the United States (Bradbrook, 1997) and a recent voluntary agreement among Western European car manufacturers to improve fuel efficiency by 25 percent between 1995 and 2008. In nearly all countries, cars owned by companies or public authorities are often inappropriately powered. Bad driving habits, especially of government- and company-owned vehicles, also impede the rational use of energy in road transportation.

The benefits of fuel efficiency standards are evident from the success of mandatory Corporate Average Fuel Economy (CAFE) standards being introduced in North America (though the standards do not apply to light vehicles). Many voters in *OECD countries* consider driving a car to be an expression of individual freedom. As a result most drivers and politicians do not pay much attention to fuel efficiency.

The weak finances of local and national governments in *transition economies* make it difficult to introduce modern public transport systems or to upgrade existing ones. The limited financial resources of households and small companies are the main reason for

heavy imports of used cars from Western Europe and Japan.

In *developing countries* road transportation increases mobility without the huge public upfront investment needed for railways, subways, and trams. Thus one major obstacle to improved energy efficiency is the limited number of alternative transport modes. In many developing countries vehicles are either assembled or imported. Economic problems and devaluations of local currencies have driven up vehicle prices. As a result many people and small firms cannot afford new vehicles, so a lot of car buyers opt for imported used vehicles that have been used for several years in the country of origin. Similar problems are being encountered with the pricing of spare parts. In addition, most developing countries lack regulation on regular car inspections. Together these problems have resulted in poor vehicle maintenance that has exacerbated energy inefficiency.

The Intergovernmental Panel on Climate Change report on aviation (IPCC, 1999a) projects a 20 percent improvement in fuel efficiency by 2015 and a 40 percent improvement by 2050 relative to aircraft produced today. Improvements in air traffic management would reduce fuel demand by another 8-18 percent. Environmental levies and emissions trading can help realise these improvements by encouraging technological innovation and reducing the growth in demand for air travel.

Agriculture. Agriculture is the main beneficiary of subsidised electricity in *developing countries.* In some cases electricity is even provided to agricultural consumers free of charge. One major fallout of this approach is the phenomenal growth in electricity consumption by this sector. In the 1980s agriculture consumed 18 percent of India’s electricity; by 1994 it consumed 30 percent (CMIE, 1996). Even after accounting for the additional pump sets installed during this period, extremely low electricity prices are one of the main reasons for the increase in the sector’s energy intensity.

Cogeneration. Cogeneration has considerable potential in industrial sites and district

heating systems. Yet the monopolistic structure of the electricity sector in many countries has led to high prices for maintenance and peak power, rather low buyback rates and costly technical standards for grid connection, and to dumping prices in the case of planning new cogeneration capacity (VDEW, 1997). As a result many auto producers restrict the capacity of the cogeneration plant to their minimum electricity and heat needs, although they may wish to produce more heat by cogeneration. This situation is changing now in countries (such as France) with liberalised electricity markets and regulated or competitive buyback rates.

In *Central and Eastern Europe* centralised district heating remains a widespread solution for heating big housing estates. The economics of centralising the heat supply of a certain area is regarded not as a question of profitability, but a historical fact. But inadequate pricing, inefficient operation, mismanagement, and lack of full use of cogeneration potential are encouraging heat consumers to disconnect from the district heating grid. The easy availability of natural gas, existence of small and medium-size cogeneration units (namely, gas engines and gas turbines), and desire for independence also encourage consumers to disconnect. This tends to make the heat demand density leaner, driving the system in a negative spiral that may end in the economic collapse of many district heating enterprises in transition economies.

Low incomes make it difficult for households in developing countries to switch from lower efficiency to higher efficiency (but more expensive) devices.

The potential for industrial cogeneration is estimated at 20-25 percent of industrial and commercial electricity demand in several *developing countries* (TERI, 1994; Alnakeeb,

1998). India’s sugar industry, for instance, generates 3,500 megawatts of bagasse-based cogenerated power. But the full potential of industrial cogeneration in China, India, and Latin America has yet to be realised because of slow progress on power buyback arrangements and the wheeling and banking of cogenerated power by state electricity boards. Although institutional barriers are considered the main obstacle in this regard, limited indigenous capacity to manufacture high-pressure boilers and turbines is also an important barrier, as hard currency is scarce in developing countries (TERI, 1994).

For every obstacle and market imperfection discussed in this section, there are interrelated measures of energy efficiency policy that could remove or reduce them (figure 6.5). But the choice of which policies to pursue must be made with care, because their effectiveness depends on many regional, cultural, and societal circumstances and on the different weights of the obstacles in different regions.

National and international policies to exploit the economic potential of energy efficiency in end-use sectors

Despite the clear warnings of the scientific community (IPCC, 1995) and the commitments made under the Kyoto Protocol, and despite possible reductions in energy costs and the benefits of energy efficiency for employment and economic development (see box 6.3), many scientists and non-governmental organisations (NGOs) feel that “policy makers are still doing too little to use energy efficiency potentials in order to safeguard their citizens and their future” (Lovins and Hennicke, 1999, pp. 7-10; Phylipsen, Blok, and Hendriks, 1999; further citations).[27] These authors ask for more activity in policy areas such as energy efficiency, transportation, and renewables.

Over the past 25 years individual and ad hoc policy measures - such as information, training, grants, or energy taxes - have often produced limited results (Dasgupta, 1999). But integrated energy demand policies - which consider simultaneous obstacles and the

interdependence of regulations, consultations, training programmes, and financial incentives - and long-lasting programmes have been relatively successful. Energy demand policy is not only initiated by governments. Companies, utilities, industrial associations, and NGOs may also play an important part.

An integrated energy, transportation, financial, and economic policy is one of the main opportunities for realising the huge economic energy saving potentials not only of individual parts and technologies, but also of a country's energy-using systems. There is a strong need to formulate a long-term strategy that promotes energy efficiency improvements in all sectors of the economy and that takes into account general obstacles, market imperfections, and target group-specific barriers. This section presents the policy initiatives to be taken in different end-use sectors in a linear manner, but such initiatives have to be implemented together to contribute to sustainable development (see figure 6.5). These policies include general policy instruments such as energy taxes, direct tax credits, emissions trading, a general energy conservation law, general education on energy issues in schools, and research and development (see chapter 11). In some cases international cooperation by governments and industrial associations may play an important supporting role.

General policy measures

General policies to promote energy efficiency try to overcome general obstacles and market imperfections. They may also be implemented in the context of broader economic issues, such as shifting the tax burden from labour to non-renewable resources through an ecotax at the national or multinational level (see chapter 11). Or new regulation may be needed to limit the ambiguous impacts of liberalised electricity and gas markets in their transition phase.

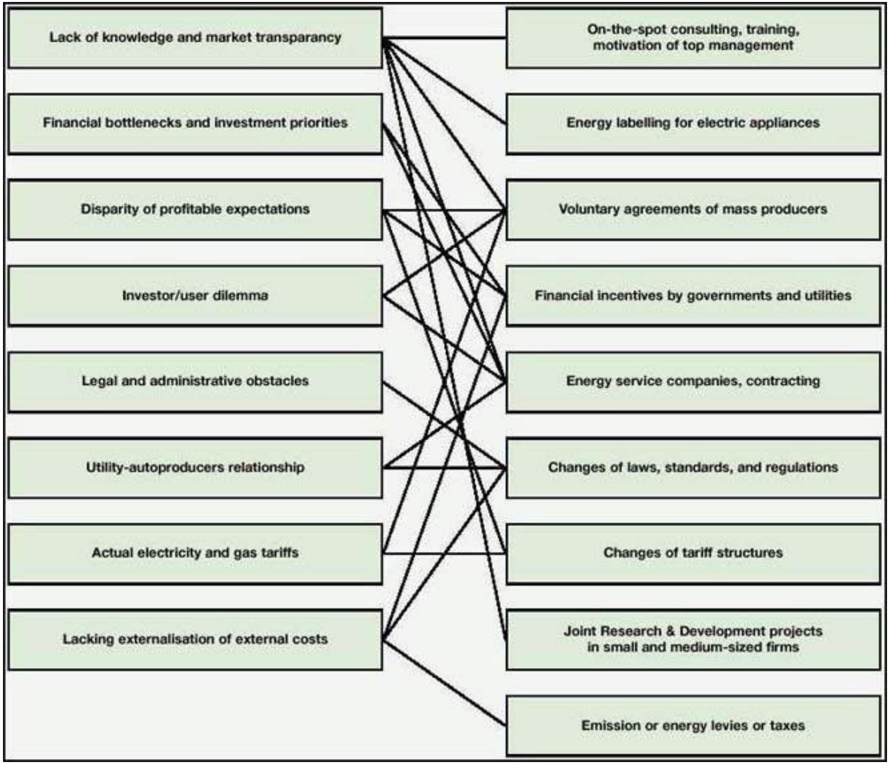


FIGURE 6.5. OBSTACLES AND MARKET IMPERFECTIONS FOR ENERGY EFFICIENCY AND RELATED POLICIES: A SCHEME FOR POLICY OPTIONS AND INTEGRATED EFFICIENCY POLICY

The acceptance of such policy measures differs by country and varies over time depending on how much an energy policy objective is violated or in question. Energy efficiency policy

was widely accepted in OECD countries in the 1970s and early 1980s, when dependence on oil imports from OPEC countries was high and higher fuel prices had changed cost structures and weakened competitiveness in energy-intensive industries. With declining world energy prices between 1986 and 1999, reduced dependence on energy imports in many OECD countries, and stagnating negotiations on the implementation of the Kyoto Protocol, public interest in energy efficiency policy has fallen in many OECD countries.

By contrast, energy efficiency receives considerable attention from governments, industries, and households in Eastern European countries, in some Commonwealth of Independent States countries without indigenous energy resources, and in many emerging economies facing problems with sufficient and reliable supplies of commercial energy.

Energy conservation laws have been passed in many countries (Australia, Canada, China, Finland, Germany, Japan, Russia, Switzerland, the United States) or are in the process of being passed (India). Such laws are important for establishing a legal framework for sector regulation (building codes, labelling, technical standards for equipment and appliances) and for implementing other measures (energy agencies, financial funds for economic incentives or public procurement). In many countries with federal structures, however, much of the legislative power to enact energy conservation laws rests with individual states - posing problems for compliance and joint action.

Education on energy efficiency issues in primary or secondary schools, along with professional training, raises consciousness and basic knowledge about the efficient use of energy and the most recent technologies.

Direct subsidies and tax credits were often used to promote energy efficiency in the past. Direct subsidies often suffer from a free-rider effect when they are used for investments that would have been made anyway. Although it is difficult to evaluate this effect, in Western Europe 50-80 percent of direct subsidies are estimated to go to free riders (Farla

and Blok, 1995). Low-interest loans for energy efficiency projects appear to be a more effective subsidy, although they may have a distribution effect.

Energy service companies are a promising entrepreneurial development, as they simultaneously overcome several obstacles by providing professional engineering, operational, managerial, and financial expertise, along with financial resources. Such companies either get paid a fee based on achieved savings or sign a contract to provide defined energy services such as heating, cooling, illumination, delivery of compressed air, or hot water.

Energy demand policy is not only initiated by governments. Companies, utilities, industrial associations, and NGOs may also play an important part.

Transition economies. From a policy perspective, efficient energy use creates enormous opportunities in light of huge reinvestments in industry and infrastructure and large new investments in buildings, vehicles, and appliances. In the Commonwealth of Independent States and Eastern Europe increased energy efficiency was made a top political priority in the early and mid-1990s - as with Russia’s 1994 National Energy Strategy (IEA, 1995). But according to the Russian Federation Ministry of Fuel and Energy (1998), government support for such activities was less than 8 percent of the planned funding in 1993-97.

Transition economies that were relatively open under central planning (defined as those for whom foreign trade accounted for more than 30 percent of GDP) have had an easier time adjusting to world markets. Multinational companies from Western Europe and other OECD countries maintain their technical standards when building new factories in transition economies. In addition, Eastern European countries are trying to approach (and

later, to meet) Western European technical standards as part of their eventual accession to the European Union (Krawczynski and Michna, 1996; Michna, 1994).

Energy efficiency policies developed differently according to the speed of transition and economic growth in these countries. Some elements of efficiency programmes have been quite successful despite economic difficulties: laws, energy agencies, energy auditing of federal buildings. In most transition economies the first energy service companies were established with the support of international institutions. Some industrial enterprises established internal energy monitoring and control, reinforced by incentives and sanctions for particular shops and their management. The results of such activities differed considerably among transition economies, reflecting levels of organisation, human and financial capital, trade experience, foreign investment, energy subsidies, and other factors.

Developing countries. The phasing out of substantial energy subsidies can often be complemented by capacity building, professional training, and design assistance. Utilities in Mexico and Brazil, for example, have been active in demand-side management programmes with cost-benefit ratios of more than 10 to 1 (Dutt and others, 1996). Given the shortage of capital in many developing countries, financial incentives seem to have a large impact on energy efficiency (unlike in OECD countries). An example is China in the 1980s, where such incentives contributed to the remarkable decline in China’s industrial energy intensity (Sinton and Levine, 1994).

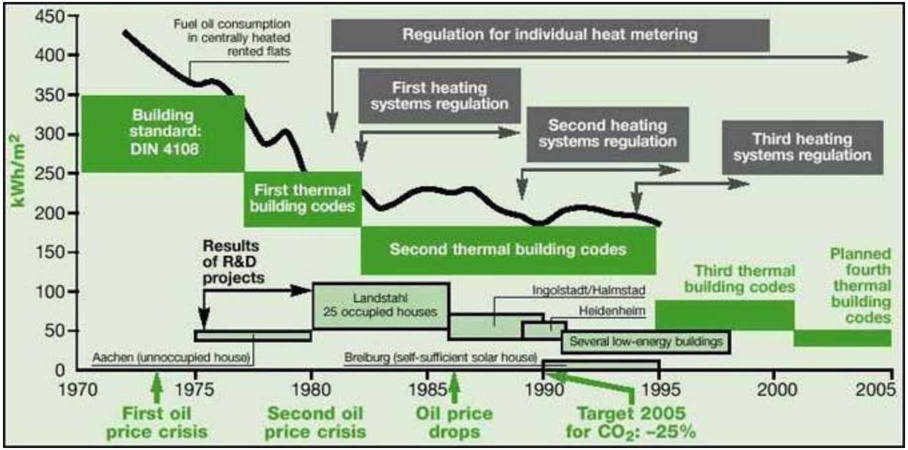
Sector- and technology-specific policy measures

Given the many obstacles that keep economic energy-saving potential from being realised on a sectoral or technological level, any actor will look for a single instrument that can alleviate all obstacles. For mass products, performance standards are considered an efficient instrument because they can be developed after discussions with scientists, engineers, and industrial associations, manufacturers, and importers. Standards and

labelling avoid the need for information, high transaction costs, and dissemination to, consultations with, and training of millions of households, car drivers, and small and medium-size companies (Natural Resources Canada, 1998).

BOX 6.12. THE MULTIMEASURE CHARACTER OF NATIONAL ENERGY EFFICIENCY POLICY - A 20-YEAR LEARNING CURVE FOR MULTIFAMILY BUILDINGS IN WEST GERMANY

After the oil shocks of the 1970s, German professional organisations made recommendations for new building standards. In addition, the federal government enacted an ordinance for boiler efficiencies to accelerate the replacement of old boilers by new, more efficient ones. Building codes and boiler standards have since been tightened three times, and regulations on individual heat metering were introduced in the early 1980s. Research and development enabled the new standards to be met. Twenty-five years later, the results are convincing. New buildings are 50-70 percent more efficient, and retrofits have cut energy consumption by 50 percent in Germany (and by at least 30 percent in most Western European countries).



Interrelation between research to lower costs, proof of technical feasibility, and heating and insulation regulation in Germany

Source: EC, 1999b.

But no single, highly efficient instrument will be available in all cases (as with the refurbishing of buildings or efficiency improvements in industrial plants). In these cases a package of policy measures has to be implemented to alleviate obstacles (see figure 6.5).

Buildings. There seems to be an intellectual barrier between planners and architects for buildings in cold and warm climates, although building codes may offer huge efficiency potential in most countries. Jochem and Hohmeyer (1992) conclude that if comprehensive policy strategies are implemented, governments will discover that the economics of end-use efficiency are far more attractive than is currently believed. A good example is the refurbishing of residential buildings. Homes and apartment buildings consume about 20 percent of final energy in many countries. Refurbishing a building may be primarily an individual event, but its effectiveness depends on such political and social remedies as:

- **Advanced education and training of architects, planners, installers, and builders, as carried out in the Swiss ‘impulse programme’, which has had outstanding results since 1978.**

- **Information and education for landlords and home owners (particularly on the substitution of energy costs for capital costs).**

- **Training professional advisers to perform audits and provide practical recommendations. These audits should be subsidised; otherwise they may be considered too costly by landlords or home owners. Such subsidies have proven cost-effective.**

- **Investment subsidies tied to a registered energy consultant and a formal heat survey report and minimum energy efficiency level.**

- **Investment subsidies for specific groups of home owners or multifamily buildings to overcome financial bottlenecks or risks of the investor-user dilemma. The cost-effectiveness of such subsidies has often been overestimated, however.**

- **Economically justified insulation and window design secured by new building codes that also cover the refurbishing of buildings.**

- **Research and development to improve building design (low-energy houses, passive solar buildings), insulation material, or windows, or to reduce construction costs.**

Energy-saving programs in Denmark, Finland, Germany, Sweden, and Switzerland owe much of their success to this multimeasure approach, which is increasingly being adopted by other countries (box 6.12). The combination of measures has increased capacity in the construction sectors of those countries. Energy labelling for buildings has been introduced in a few OECD countries and is being considered in several others (Bradbrook, 1991). Such labelling provides information on a building’s energy costs when it is being rented or bought (Hicks and Clough, 1998). Building standards for cooling have been adopted in Indonesia, Mexico, Singapore, and Thailand. Compliance with building codes is uncertain in many countries, however, because (expensive) controls are lacking (Duffy, 1996).

Household appliances and office automation. Household appliances and office equipment are well suited for technical standards and labelling. Varone (1998) compared instruments used between 1973 and 1997 in Canada, Denmark, Sweden, Switzerland, and the United States to promote energy-efficient household appliances and office equipment. About 20 instruments were identified (table 6.14). Various attempts have been made in the past 10 years to coordinate and harmonise policies at an international level. Some analysts

consider international cooperation to be the only real means for inducing a market transformation in office equipment. Varone and Aebischer (1999) prefer to keep a diversity of instruments in different countries - an approach that allows for the testing of new instruments, offers the possibility of testing diverse combinations of instruments, and takes advantage of political windows of opportunity specific to each country (as with the Energy Star Program for office equipment in the United States) (Geller, 1995).

Some *developing countries* (China, India) try to follow OECD policies on technical standards and energy labelling. OECD governments should be aware of this implication (box 6.13).

Small and medium-sized companies and public administrations. Small and medium-sized companies and public administrations are typical targets when several policy measures have to be taken simultaneously: professional training, support for initial consulting by external experts, demonstration projects to increase trust in new technical solutions, energy agencies for several tasks (see above), and soft loans. These companies and administrations are also affected by standards for labelling and for cross-cutting technologies such as boilers and electrical motors and drives (Bradbrook, 1992).

This policy mix seems to be successful for this target group in almost all countries. In Russia and most Eastern European countries, energy agencies are responsible for energy efficiency initiatives in end-use sectors. These agencies are playing an important role, supported by energy service companies that provide financial and technical assistance to realise the identified potentials. Brazil and Mexico have also established national agencies for energy efficiency (see box 6.8). With the privatisation of Brazilian utilities, the new concessionaires are required to spend 1 percent of their revenues (less taxes) on energy efficiency, with 0.25 percent specifically for end-use efficiency measures.

Big enterprises and public administrations. Big enterprises and public administrations

have specialised staff and energy managers, but they still need specific policy measures to achieve their economic potential. The government of India occasionally uses expert committees to develop policy recommendations. The reports of the committees include several recommendations to encourage energy efficiency improvements (box 6.14). A ‘minister’s breakfast’ is a key tool for motivating top managers of companies and administrations and for raising awareness of energy efficiency potential. In addition, keynote speakers at the annual meetings of industrial associations can help convey positive experiences with new efficient technologies among the responsible middle managers.

BOX 6.13. FAST TRANSMISSION OF EFFICIENCY PROGRAMMES FROM OECD TO DEVELOPING COUNTRIES: THE CASE OF EFFICIENT LIGHTING

Mexico was the first developing country to implement a large-scale energy-efficient lighting programme for the residential sector. The programme was funded by the Mexican Electricity Commission, ($10 million), the Global Environment Facility ($10 million), and the Norwegian government ($3 million). Between 1995 and 1998 about 1 million compact fluorescent lamps were sold in the areas covered by the programme. Use of the lamps avoided 66.3 megawatts of peak capacity and resulted in monthly energy savings of 30 gigawatt-hours. Given the lifetime of the efficient lamps, the impacts of the programme are expected to last until 2006 (Padilla, 1999).

Economic evaluations show positive returns to households, the power sector, and society. The programme, ILUMEX (Illumination of Mexico), has also helped generate direct and indirect jobs, training and building indigenous capacity to design and implement large-scale efficiency programmes (Vargas Nieto, 1999). Smaller residential energy-efficient lighting programmes have been introduced in other Latin American countries, including Bolivia, Brazil, Costa Rica, Ecuador, and Peru.

Local governments should consider using life-cycle costs and increasing flexibility

between investment and operating budgets. This move may require changes in legislation in some countries.

TABLE 6.14. POLICIES TO INCREASE EFFICIENCY IN ELECTRIC APPLIANCES AND OFFICE EQUIPMENT, VARIOUS OECD COUNTRIES

Area	**Canada**	**Denmark**	**Sweden**	**Switzerland**	**United States**
Household appliances	Mandatory labelling (1978) Standards (1992)	Mandatory labelling (1982) Standards (1994)	Mandatory labelling (1976) Technology procurement (1988)	Negotiated target values (1990) Voluntary labelling (1990)	Voluntary labelling (1973) Negotiated target values (1975) Mandatory labelling (1975) Standards (1978) Technology procurement (1992)
Office equipment				Negotiated target values (1990) Quality labelling (1994) Public purchasing (1994)	Quality labelling (1992) Public purchasing (1993)

Source: Varone 1998, p. 143.

Transportation. Policies on road transportation may include efficiency standards for vehicles imposed by national governments or technical objectives achieved through

voluntary agreements among car manufacturers and importers (Bradbrook, 1994). Similar measures can be taken by aeroplane, truck, and bus manufacturers. High fuel taxes in countries with low taxation may support technical progress. A more systemic view relates to several areas of transport systems and policy measures (IEA, 1997a):

- **Subsidies for mobility (such as for daily commuting, national airlines, or public urban transport) increase the demand for transportation, especially road transport, and should be removed where socially acceptable. An untaxed benefit for employees driving a car bought by companies or institutions should also be removed.**

- **Road user charges and parking charges may reduce driving in cities, cut down on congestion and road accidents, and shift some mobility to public transport. Car sharing also has implications for car use and occupancy levels.**

- **It is possible to lower the cost of public transport through automation and international procurement, as is a better organisation of rail freight crossing national borders.**

- **In the long term, intelligent city planning that does not divide an urban area by functions and related sections creates substantial potential for reduced mobility.**

BOX 6.14. ENERGY EFFICIENCY POLICY RECOMMENDATIONS BY EXPERT COMMITTEES FOR COMPANIES IN INDIA

Technical and operational measures

- Detailed energy audit should be made mandatory in all large and medium-sized enterprises.

- Potential cogeneration opportunities should be identified and pursued by providing financial assistance

- Energy consumption norms should be set for each industry type and penalties and rewards instituted based on the performance of the industry.

Fiscal and economic measures

- Creation of an energy conservation fund by levying energy conservation taxes on industrial consumption of petroleum products, coal, and electricity.

- Customs duty relief on energy conservation equipment.

Energy pricing

- Energy pricing policies must ensure that sufficient surplus is generated to finance energy sector investments, economical energy use is induced, and interfuel substitution is encouraged.

Industrial licensing, production, and growth

- Before licenses are given to new units, the capacity of existing units and the capacity use factor should be taken into consideration.

- In setting up new units, the technology should be the least energy-intensive option.

- The possibility of using waste heat from power plants by setting up appropriate industries in the vicinity should be considered.

Organisational measures

- The appointment of energy managers in large and medium-sized industries should be mandatory. For small-scale enterprises, a mechanism should be instituted for energy auditing and reporting.

Energy equipment

- Better standards should be set for energy-consuming equipment.

- Restrictions must be placed on the sale of low-efficiency equipment.

- Manufacture of instruments required to monitor energy flows must be encouraged. Imports of such instruments and spare parts should be free of customs duty.

Research and development

- Each industrial process should be reviewed to identify the research and development required to reduce energy consumption.

- Research and development on energy efficiency should be sponsored by the government as a distinct component of the science and technology plan.

Other measures

- Formal training to develop energy conservation expertise should be introduced in technical institutions.

- The government should recognise and honour individuals and organisations for outstanding performance on energy conservation.

- Efforts to raise awareness on energy conservation should be intensified.

Source: Bhattacharjee, 1999.

In *higher-income developing countries* there are concerns that a shift from fuel-efficient to fuel-inefficient transport is threatening the oil security of these countries. To address these concerns, policies should encourage a shift from road transport to subways and rail transport by reducing travel times and increasing the costs of road transportation. These countries should also search for new financing to replace old bus fleets.

Agriculture. Two main issues affect the energy efficiency of agriculture in *developing countries.* The first is related to subsidised electricity tariffs for this sector; the second is the use of highly inefficient prime movers for agricultural pump sets and the ineffective configuration in which they are often used. Increases in electricity tariffs should be accompanied by free consultation by experts and an expansion of credit and savings schemes to help rural people keep their energy costs at an acceptable level. Efficient prime movers and appliances and organisational measures in water use efficiency and irrigation management would help achieve that goal.

Cogeneration. Liberalisation of the electricity market may have different implications for cogeneration in different countries (Jochem and Tnsing, 1998; AGFW, 2000). Earlier obstacles, such as low buyback rates and high rates for maintenance and emergency power, are alleviated by competition. But a legal framework for wheeling and public control seems to be necessary to level the playing field, particularly during the adaptation phase of liberalisation and for small and medium-size cogeneration plants of independent power producers. Lack of expertise and the trend of outsourcing cogeneration plants in industry can be addressed by supporting energy service companies with training, standardised contracts for small units, and deductions on fuels for cogeneration.

Maintaining energy-efficient cogeneration with district heating in *industrialised and transition economies* requires determination, a legal framework, technical and economic

skills, and financial resources. Several steps are needed to make or to keep centralised district heating systems competitive:

- **A possibility of switching between fuels (lowering gas prices by switching to storable oil in the coldest 100-200 hours of the winter) and using cheap fuel (‘puffer’ gas, coal, municipal solid waste, garbage incineration, sewage treatment biogas).**
- **Proper and economic sharing of heat generation between centralised heat units and peak load boilers, and an increase in the electricity production planted on the given heat demand by turning to higher parameters in the power-generating cycle (such as combined gas and steam cycles).**
- **Better performance control of the heating system, variable mass-flow in addition to temperature control in hot water systems, lower temperatures in the heating system, and the use of heat for cooling (through absorption techniques) to improve the seasonal load of the system.**
- **One-by-one metering and price collection for consumers in transition economies.**
- **A minimum buyback rate for cogenerated electricity in the adaptation phase of liberalisation (AGFW, 2000).**

Such a bundle of measures can assure the competitiveness of other options and the realisation of the huge potential for cogeneration in centralised heating systems.

In *developing countries* a lack of knowledge, capital, and hard currency may constrain cogeneration investments. Thus policy measures and incentives are often needed - and were recommended, for example, by a task force in India in 1993. The Ministry of Non-Conventional Energy Sources launched a national programme promoting bagasse-based

cogeneration. The process of agreeing on mutually acceptable buyback rates and wheeling of power by state electricity boards is still under way, but there is hope that the institutional barriers will give way to large-scale cogeneration, particularly in liberalised electricity markets.

International policy measures

The globalisation of many industrial sectors creates enormous potential for improving energy efficiency at the global scale. Harmonising technical standards for manufactured goods offers new opportunities for economies of scale, lowering the cost of energy-efficient products. To avoid the import of energy-inefficient products, governments, associations of importers, and NGOs may consider negotiating efficiency standards for appliances and other mass-produced products imported from industrialised countries. Imported vehicles, used cars, buses, and trucks should not be more than five or six years old (as in Bangladesh and Hungary). Similar rules could be introduced for major imported and energy-intensive plants.

The Energy Charter Protocol on Energy Efficiency and Related Environmental Aspects entered into force in April 1998. The protocol is legally binding but does not impose enforceable obligations on nations to take specified measures. It is a 'soft law' requiring actions such as:

- **Formulating aims and strategies for improving energy efficiency and establishing energy efficiency policies.**
- **Developing, implementing, and updating efficiency programmes and establishing energy efficiency bodies that are sufficiently funded and staffed to develop and implement policies.**
- **Creating the necessary legal, regulatory, and institutional environment for energy**

efficiency, with signatories cooperating or assisting each other in this area.

The protocol received significant political support from the EU Environmental Ministers Conference in June 1998. By December 1998, however, it had only about 40 signatories, mainly Western European countries and transition economies. Thus it has no world-wide support (Bradbrook, 1997).

The globalisation of many industrial sectors creates enormous potential for improving energy efficiency at the global scale.

Commitments to the Kyoto Protocol by Annex B countries are a major driver of energy efficiency, as about 70 percent of these countries' greenhouse gas emissions are related to energy use. Although energy efficiency is a major contributor for achieving the targets of the protocol, there are few references to it in the text of the document. Ratification of the protocol and implementation of the flexible instruments will be important for developing policy awareness in industrialised countries of the substantial potential that improved energy efficiency offers for meeting the objectives.

Better air traffic management will likely reduce aviation fuel burn by some 10 percent if fully implemented in the next 20 years - provided the necessary international regulatory and institutional arrangements have been put in place in time. Stringent aircraft engine emission and energy efficiency regulations or voluntary agreements among airlines can expedite technological innovations. Efforts to remove subsidies, impose environmental levies (charges or taxes), and promote emissions trading could be negotiated at the international level (IPCC, 1999b). These economic policies - though generally preferred by industry - may be highly controversial.

Conclusion

As the long-term potential for energy efficiency reduces useful energy demand and the proceeding levels of energy conversion, future energy policy of most countries and on the international level will have to broaden substantially its scope from energy supply to energy services. This kind of policy will be much more demanding in designing target group-specific and technology-specific bundles of policy measures. But the success of this new policy process will be worth the effort from the economic, social and environmental perspective.

Notes

1. Lee Schipper was the lead author of this section.

2. Eberhard Jochem was the lead author of this box.

3. Inna Gritsevich and Eberhard Jochem were the lead authors of this section.

4. Anthony Adegbulugbe was the lead author of this section.

5. Somnath Bhattacharjee was the lead author of this section.

6. Eberhard Jochem was the lead author of this section.

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8. Bernard Aebischer and Eberhard Jochem were the lead authors of this section.

9. Ernst Worrell, Allen Chen, Tim McIntosch, and Louise Metirer were the lead authors of this section.

10. This means that the cost-effective potential is probably equivalent to the microeconomic potential (see the introduction to the section on potential economic benefits).

11. The estimates of the economic potential are based on supply curves for each sector developed by Bailie and others (1998). It is unclear what discount rate was used to estimate the economic potential. Hence we cannot determine if the study estimates a microeconomic or macroeconomic potential (see box 6.2).

12. It is unclear what discount rate was used to estimate the economic potential. In some economic assessments in this report a discount rate of 50 percent is used for investments in the transportation sector.

13. Bidyut Baran Saha and David Bonilla were the lead authors of this section.

14. Tamas Jaszay was the lead author of this section.

15. Inna Gritsevich was the lead author of this section.

16. Somnath Bhattacharjee was the lead author of this section.

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25. Somnath Bhattacharjee, Gilberto Jannuzzi, and Fengqi Zhou were the lead authors of this section.

26. Eberhard Jochem was the lead author of this section.

27. Eberhard Jochem was the lead author of this section.

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Chapter 7. Renewable Energy Technologies

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ABSTRACT

In 1998 renewable energy sources supplied 56 ± 10 exajoules, or about 14 percent of world primary energy consumption. The supply was dominated by traditional biomass (38 ±10 exajoules a year). Other major contributions came from large hydropower (9 exajoules a year) and from modern biomass (7 exajoules). The contribution of all other

renewables - small hydropower, geothermal, wind, solar, and marine energy - was about 2 exajoules. That means that the energy supply from new renewables was about 9 exajoules (about 2 percent of world consumption). The commercial primary energy supply from renewable sources was 27 ± 6 exajoules (nearly 7 percent of world consumption), with 16 ± 6 exajoules from biomass.

Renewable energy sources can meet many times the present world energy demand, so their potential is enormous. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services (particularly in developing countries and rural areas), create new employment opportunities, and offer possibilities for local manufacturing of equipment.

There are many renewable technologies. Although often commercially available, most are still at an early stage of development and not technically mature. They demand continuing research, development, and demonstration efforts. In addition, few renewable energy technologies can compete with conventional fuels on cost, except in some niche markets. But substantial cost reductions can be achieved for most renewables, closing gaps and making them more competitive. That will require further technology development and market deployment - and boosting production capacities to mass production.

For the long term and under very favourable conditions, the lowest cost to produce electricity might be $0.01 - 0.02 a kilowatt-hour for geothermal, $0.03 a kilowatt-hour for wind and hydro, $0.04 a kilowatt-hour for solar thermal and biomass, and $0.05 - 0.06 a kilowatt-hour for photovoltaics and marine currents. The lowest cost to produce heat might be $0.005 a kilowatt-hour for geothermal, $0.01 a kilowatt-hour for biomass, and $0.02 - 0.03 a kilowatt-hour for solar thermal. The lowest cost to produce fuels might be $1.5 a gigajoule for biomass, $6 - 7 a gigajoule for ethanol, $7 - 10 a gigajoule for

methanol, and $6 - 8 a gigajoule for hydrogen.

Scenarios investigating the potential of renewables reveal that they might contribute 20 - 50 percent of energy supplies in the second half of the 21st century. A transition to renewables-based energy systems would have to rely on:

- **Successful development and diffusion of renewable energy technologies that become more competitive through cost reductions from technological and organisational developments.**

- **Political will to internalise environmental costs and other externalities that permanently increase fossil fuel prices.**

Many countries have found ways to promote renewables. As renewable energy activities grow and require more funding, the tendency in many countries is to move away from methods that let taxpayers carry the burden of promoting renewables, towards economic and regulatory methods that let energy consumers carry the burden.

Renewable energy sources have been important for humans since the beginning of civilisation. For centuries and in many ways, biomass has been used for heating, cooking, steam raising, and power generation - and hydropower and wind energy, for movement and later for electricity production. Renewable energy sources generally depend on energy flows through the Earth's ecosystem from the insolation of the sun and the geothermal energy of the Earth. One can distinguish:

- **Biomass energy (plant growth driven by solar radiation).**
- **Wind energy (moving air masses driven by solar energy).**
- **Direct use of solar energy (as for heating and electricity production).**
- **Hydropower.**
- **Marine energy (such as wave energy, marine current energy, and energy from**

tidal barrages).
- **Geothermal energy (from heat stored in rock by the natural heat flow of the Earth).**

Many renewables technologies are suited to small off-grid applications, good for rural, remote areas, where energy is often crucial in human development.

If applied in a modern way, renewable energy sources (or renewables) are considered highly responsive to overall energy policy guidelines and environmental, social, and economic goals:

- **Diversifying energy carriers for the production of heat, fuels, and electricity.**
- **Improving access to clean energy sources.**
- **Balancing the use of fossil fuels, saving them for other applications and for future generations.**
- **Increasing the flexibility of power systems as electricity demand changes.**
- **Reducing pollution and emissions from conventional energy systems.**
- **Reducing dependency and minimising spending on imported fuels.**

Furthermore, many renewables technologies are suited to small off-grid applications, good for rural, remote areas, where energy is often crucial in human development. At the same time, such small energy systems can contribute to the local economy and create local jobs.

The natural energy flows through the Earth’s ecosystem are immense, and the theoretical potential of what they can produce for human needs exceeds current energy consumption by many times. For example, solar power plants on 1 percent of the world’s desert area

would generate the world's entire electricity demand today. With ample resources and technologies at hand for renewable energy use, the question of future development boils down to economic and political competitiveness with other energy sources. Since the performance and costs of conversion technologies largely determine the competitiveness of renewables, technological development is the key. Still, the World Energy Council, Shell, the Intergovernmental Panel on Climate Change (IPCC), and several UN bodies project a growing role for renewable energy in the 21st century with major contributions from biomass, hydropower, wind, and solar.

TABLE 7.1. CATEGORIES OF RENEWABLE ENERGY CONVERSION TECHNOLOGIES

Technology	Energy product	Application
Biomass energy		
Combustion(domestic scale)	Heat (cooking, space heating)	Widely applied; improved technologies available
Combustion(industrial scale)	Process heat, steam, electricity	Widely applied; potential for improvement
Gasification/power production	Electricity, heat (CHP).	Demonstration phase
Gasification/fuel production	Hydrocarbons, methanol, H_2	Development phase
Hydrolysis and fermentation	Ethanol	Commercially applied for sugar/starch crops; production from wood under development
Pyrolysis/production of liquid fuels	Bio-oils	Pilot phase; some technical barriers
Pyrolysis/production	Charcoal	Widely applied; wide range of efficiencies

of solid fuels		
Extraction	Biodiesel	Applied; relatively expensive
Digestion	Biogas	Commercially applied
Wind energy		
Water pumping and battery charging	Movement, power	Small wind machines, widely applied
Onshore wind turbines	Electricity	Widely applied commercially
Offshore wind turbines	Electricity	Development and demonstration phase
Solar energy		
Photovoltaic solar energy conversion	Electricity	Widely applied; rather expensive; further development needed
Solar thermal electricity	Heat, steam, electricity	Demonstrated; further development needed
Low-temperature solar energy use	Heat (water and space heating, cooking, drying) and cold	Solar collectors commercially applied; solar cookers widely applied in some regions; solar drying demonstrated and applied
Passive solar energy use	Heat, cold, light, ventilation	Demonstrations and applications; no active parts
Artificial photosynthesis	H_2 or hydrogen rich fuels	Fundamental and applied research
Hydropower	Power, electricity	Commercially applied; small and large scale applications
Geothermal energy	Heat, steam, electricity	Commercially applied

Marine energy		
Tidal energy	Electricity	Applied; relatively expensive
Wave energy	Electricity	Research, development, and demonstration phase
Current energy	Electricity	Research and development phase
Ocean thermal energy conversion	Heat, electricity	Research, development, and demonstration phase
Salinity gradient/osmotic energy	Electricity	Theoretical option
Marine biomass production	Fuels	Research and development phase

BOX 7.1. LAND USE REQUIREMENTS FOR ENERGY PRODUCTION

Biomass production requires land. The productivity of a perennial crop (willow, eucalyptus, switchgrass) is 8 - 12 tonnes of dry matter per hectare a year. The lower heating value (LHV) of dry clean wood amounts to about 18 gigajoules a tonne; the higher heating value about 20 gigajoules a tonne. Thus 1 hectare can produce 140 - 220 gigajoules per hectare a year (LHV; gross energy yield; taking into account energy inputs for cultivation, fertiliser, harvest, and so on, of about 5 percent in total). The production of 1 petajoule currently requires 4,500 - 7,000 hectares. To fuel a baseload biomass energy power plant of 600 megawatts of electricity with a conversion efficiency of 40 percent would require 140,000 - 230,000 hectares. Annual production of 100 exajoules (one-quarter of the world’s current energy use) would take 450 - 700 million hectares.

A wide variety of technologies are available or under development to provide inexpensive, reliable, and sustainable energy services from renewables (table 7.1). But the stage of development and the competitiveness of those technologies differ greatly. Moreover,

performance and competitiveness are determined by local conditions, physical and socioeconomic, and on the local availability of fossil fuels.

All renewable energy sources can be converted to electricity. Since some major renewable energy sources are intermittent (wind, solar), fitting such supplies into a grid creates challenges. This is less of a problem for biomass, hydropower, and geothermal. Only a few of them produce liquid and gaseous fuels as well as heat directly.

Biomass energy

Biomass is a rather simple term for all organic material that stems from plants (including algae), trees, and crops. Biomass sources are therefore diverse, including organic waste streams, agricultural and forestry residues, as well as crops grown to produce heat, fuels, and electricity (energy plantations).

Biomass contributes significantly to the world's energy supply - probably accounting for 45 ± 10 exajoules a year (9 - 13 percent of the world's energy supply; IEA, 1998; WEC, 1998; Hall, 1997). Its largest contribution to energy consumption - on average between a third and a fifth - is found in developing countries. Compare that with 3 percent in industrialised countries (Hall and others, 1993; WEC, 1994b; IEA REWP, 1999).

Dominating the traditional use of biomass, particularly in developing countries, is firewood for cooking and heating. Some traditional use is not sustainable because it may deprive local soils of needed nutrients, cause indoor and outdoor air pollution, and result in poor health. It may also contribute to greenhouse gas emissions and affect ecosystems (chapters 3 and 10). The modern use of biomass, to produce electricity, steam, and biofuels, is estimated at 7 exajoules a year. This is considered fully commercial, based on bought biomass or used for productive purposes. That leaves the traditional at 38 ± 10 exajoules a year. Part of this is commercial - the household fuelwood in industrialised countries and charcoal and firewood in urban and industrial areas in developing countries.

But there are almost no data on the size of this market. If it can be estimated at between 10 percent and 30 percent (9 ± 6 exajoules a year), which seems probable, the total commercial use of biomass in 1998 was 16 ± 6 exajoules.

Since the early 1990s biomass has gained considerable interest world-wide. It is carbon neutral when produced sustainably. Its geographic distribution is relatively even. It has the potential to produce modern energy carriers that are clean and convenient to use. It can make a large contribution to rural development. And its attractive costs make it a promising energy source in many regions. With various technologies available to convert biomass into modern energy carriers, the application of commercial and modern biomass energy systems is growing in many countries.

TABLE 7.2. POTENTIAL CONTRIBUTION OF BIOMASS TO THE WORLD'S ENERGY NEEDS

Source	Time frame (year)	Total projected global energy demand (exajoules a year)	Contribution of biomass to energy demand (exajoules a year)	Comments
RIGES (Johansson and others, 1993)	2025 2050	395 561	145 206	Based on calculation with the RIGES model
SHELL (Kassler, 1994)	2060	1,500 900	220 200	Sustained growth scenario Dematerialization scenario
WEC (1994a)	2050 2100	671 - 1,057 895 - 1,880	94 - 157 132 - 215	Range given here reflects the outcomes of three

				scenarios
Greenpeace and SEI (Lazarus and others, 1993)	2050 2100	610 986	114 181	A scenario in which fossil fuels are phased out during the 21st century
IPCC (Ishitani and Johansson, 1996)	2050 2100	560 710	280 325	Biomass intensive energy system development

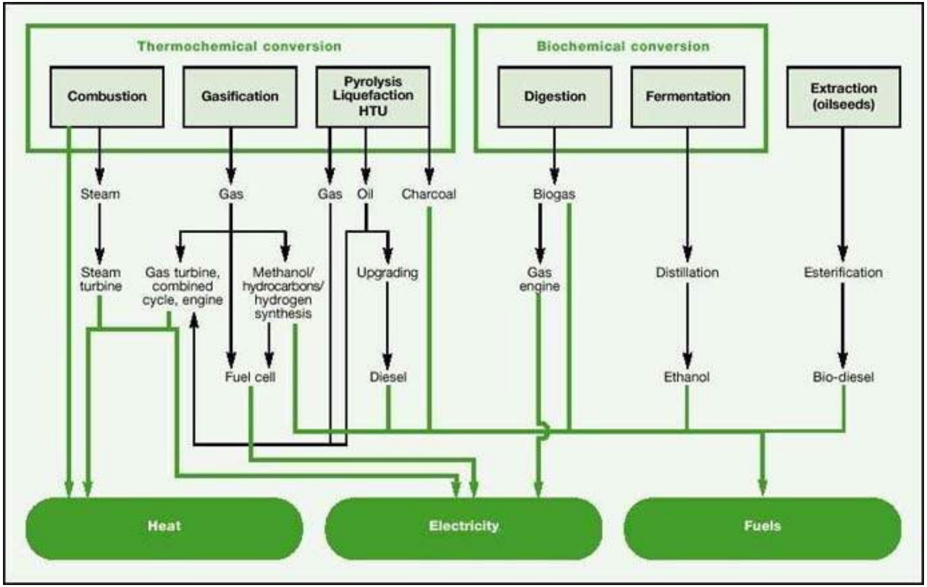

FIGURE 7.1. MAIN BIOMASS ENERGY CONVERSION ROUTES

The potential of biomass energy

The resource potential of biomass energy is much larger than current world energy consumption (chapter 5). But given the low conversion efficiency of solar to biomass energy (less than 1 percent), large areas are needed to produce modern energy carriers in substantial amounts (box 7.1). With agriculture modernised up to reasonable standards in various regions, and given the need to preserve and improve the world’s natural areas, 700 - 1,400 million hectares may be available for biomass energy production well into the 21st century (Hall and others, 1993; Larson and others, 1995; Ishitani and others, 1996; IIASA and WEC, 1998; Larson, Williams, and Johansson, 1999). This includes degraded, unproductive lands and excess agricultural lands. The availability of land for energy plantations strongly depends on the food supplies needed and on the possibilities for intensifying agricultural production in a sustainable way.

A number of studies have assessed the potential contribution of biomass to the world energy supply (table 7.2). Although the percentage contribution of biomass varies considerably, especially depending on expected land availability and future energy demand, the absolute potential contribution of biomass in the long term is high - from 100 - 300 exajoules a year. World-wide annual primary energy consumption is now about 400 exajoules.

Biomass energy conversion technologies

Conversion routes to produce heat, electricity, and/or fuels from biomass are plentiful (figure 7.1).

Production of heat. In developing countries the development and introduction of improved stoves for cooking and heating can have a big impact on biomass use (chapters 3 and 10). Especially in colder climates (Scandinavia, Austria, Germany) domestic biomass-fired heating systems are widespread. Improved heating systems are automated, have catalytic gas cleaning, and use standard fuel (such as pellets). The benefit over open fireplaces is

considerable, with advanced domestic heaters obtaining efficiencies of more than 70 percent and producing far fewer atmospheric emissions. The present heat- generating capacity is estimated to be more than 200 gigawatts of thermal energy.

Production of electricity. Some features of the main thermochemcial biomass energy conversion routes to electricity and combined heat and power (CHP) are presented in table 7.3. Combustion of biomass to produce electricity is applied commercially in many regions, with the total installed capacity estimated at 40 gigawatts of electricity. The application of fluid bed combustion and advanced gas cleaning allows for efficient production of electricity (and heat) from biomass. At a scale of 20 - 100 megawatts of electricity, electrical efficiencies of 20 - 40 percent are possible (van den Broek and others, 1996; Solantausta and others, 1996). Often the electricity is produced along with heat or steam (CHP) in Denmark and Sweden. In Southeast Asia, through the Association of Southeast Asian Nations - European Union COGEN Programme, sawmill factories in Indonesia, Malaysia, and Thailand have cogeneration systems, using wood-waste from the factories.

Co-combustion systems - combining, say, natural gas and coal with biomass - are built in such places as Denmark with the benefits of greater economies of scale and reduced fuel supply risks. Co-combustion of biomass in coal-fired power plants is a popular way to increase biomass-based power generation capacity with minimal investment (chapter 8). Other advantages over coal-based power production are the higher efficiencies (due in most cases to the large scale of the existing power plant) and lower sulphur dioxide (SO_2) and nitrogen oxide (NO_x) emissions (Meuleman and Faaij, 1999).

Large gasification. Gasification technologies can convert biomass into fuel gas, cleaned before its combustion in, say, a gas turbine. Biomass integrated gasification/combined cycle (BIG/CC) systems combine flexible fuel characteristics and high electrical efficiency. Electrical conversion efficiencies of 40 percent (LHV) are possible at a scale of about 30

megawatts of electricity (Consonni and Larson, 1994a, b; Faaij and others, 1997).

Demonstration projects are under way in various countries and for various gasification concepts. In Brazil a project supported by the World Bank and Global Environment Facility will demonstrate a 30 megawatts-electric BIG/CC unit fired with cultivated eucalyptus (Elliott and Booth, 1993). Sweden's first BIG/CC unit, based on pressurised gasification, has several thousands of hours of operational experience. Three other demonstration units around the 6 - 10 megawatts-electric scale are under way. An atmospheric BIG/CC system is being commissioned in Yorkshire, United Kingdom. In the United States an indirect gasification process is under demonstration at the Burlington power station.

The first generation of BIG/CC systems shows high unit capital costs. Depending on the scale, prices are $2,800 - 5,000 a kilowatt of electricity. But cost reduction potential is considerable for BIG/CC systems - capital costs might come down to $1,100 - 2,000 a kilowatt (Williams, 1996; Solantausta and others, 1996; Faaij, Meuleman, and Van Ree, 1998). Co-gasification of biomass, another option, is being applied in the United States and Europe. An interesting alternative for fuel gas produced through biomass gasification is its use in existing (or new) natural gas-fired combined cycles. In this way, economies of scale come with a safe fuel supply (Walter and others, 1998). This option has not been demonstrated yet, but more research is under way.

Small gasification. Small (fixed bed) gasifiers coupled to diesel or gasoline engines (typically for systems of 100 - 200 kilowatts of electricity with an approximate electrical efficiency of 15 - 25 percent) are commercially available on the market. But high costs and the need for gas cleaning and careful operation have blocked application in large numbers. Some systems are being applied fairly successfully in rural India and in China and Indonesia (Kaltschmitt and others, 1998; Stassen, 1995).

Biogas production. Anaerobic digestion of biomass has been demonstrated and applied

commercially with success in many situations and for a variety of feedstocks - such as organic domestic waste, organic industrial wastes, manure, and sludges. Large advanced systems are developed for wet industrial waste streams and applied in many countries. In India there is widespread production of biogas from animal and other wastes for cooking, lighting, and power generation (chapter 10).

TABLE 7.3. MAIN THERMOCHEMICAL BIOMASS ENERGY CONVERSION ROUTES TO HEAT AND ELECTRICITY

Conversion system	Range	Net efficiency (percent, LHV)	Investment cost (dollars a kilowatt of electricity)
Combustion			
Combined heat and power (CHP)	100 kWe to 1 MWe	60 - 90 (overall)	
	1 - 10 MWe	80 - 99 (overall)	
Standalone	20 - 100 MWe	20 - 40 (electrical)	1,600 - 2,500
Co-combustion	5 - 20 MWe	30 - 40 (electrical)	250 plus costs of existing power plant
Gasification			
CHP			900 - 3,000 (depending on location and configuration)
Diesel	100 kWe to 1 MWe	15 - 25 (electrical)	
Gas turbine	1 - 10 MWe	25 - 30 (electrical)	
BIG/CC	30 - 100 MWe	40 - 55 (electrical)	1,100 - 2,000 (when commercially proven)
Digestion			

Digestion			
Wet biomass materials	Up to several MWe	10 - 15 (electrical)	5,000

Digestion has a low overall electric conversion efficiency (roughly 10 - 15 percent, depending on the feedstock) and is particularly suited for wet biomass materials. Landfills contribute to atmospheric methane emissions. In many situations the collection of landfill gas and its conversion to electricity using gas engines is profitable, and such systems are becoming more widespread (Faaij, Hekkert, and others, 1998).

Production of liquid and gaseous fuels from biomass (bio-oil and biocrude). At temperatures around 500 degrees Celsius in the absence of oxygen, pyrolysis converts biomass to liquid (bio-oil), gaseous, and solid (charcoal) fractions. With flash pyrolysis techniques (fast pyrolysis) the liquid fraction can be up to 70 percent of the thermal biomass input. Bio-oil contains about 40 weight-percent of oxygen and is corrosive and acidic. The oil can be upgraded to reduce the oxygen content, but that has economic and energy penalties. Pyrolysis and upgrading technology are still largely in the pilot phase (Bridgewater, 1998).

Hydrothermal upgrading (HTU), originally developed by Shell, converts biomass at a high pressure and at moderate temperatures in water to biocrude. Biocrude contains far less oxygen than bio-oil produced through pyrolysis, but the process is still in a pre-pilot phase (Naber and others 1997).

Ethanol. Production of ethanol by fermenting sugars is a classic conversion route for sugar cane, maize, and corn on a large scale, especially in Brazil, France, and the United States. Zimbabwe also has a considerable fuel ethanol programme using sugar cane (Hemstock and Hall, 1995). The U.S. and European programmes convert surplus food crops to a useful(by) product. But ethanol production from maize and corn is far from being competitive with gasoline and diesel. Nor is the overall energy balance of such systems

very favourable.

An exception is Brazil’s PRO-ALCOOL programme, due to the high productivity of sugar cane (Rosillo-Calle and Cortez, 1998). This programme is discussed in some detail later in this chapter. In 1998 world production of ethanol was estimated at 18 billion litres (equivalent to 420 petajoules).

Ethanol can also be produced by the hydrolysis of lignocellulosic biomass, a potentially low-cost and efficient option. Hydrolysis techniques are gaining more development attention, particularly in Sweden and the United States, but some fundamental issues need to be resolved. If these barriers are lowered and ethanol production is combined with efficient electricity production from unconverted wood fractions (such as lignine), ethanol costs could come close to current gasoline prices - as low as $0.12 a litre at biomass costs of about $2 a gigajoule (Lynd, 1996). Overall system conversion efficiency could go up to about 70 percent (LHV).

Esters from oilseeds. Oilseeds, such as rapeseed, can be extracted and converted to esters and are well suited to replace diesel. Substantial quantities of RME (rape methyl esters) are produced in the European Union and to a lesser extent in North America. But RME requires substantial subsidies to compete with diesel. Energy balances for RME systems are less favourable than those for perennial crops (Ishitani and Johansson, 1996), so the net energy production per hectare is low. These balances can be improved if by-products (such as straw) are also used as an energy source.

Biomass has gained considerable interest world-wide. It is carbon neutral when produced sustainably.

Methanol, hydrogen, and hydrocarbons through gasification. Production of methanol and hydrogen using gasification technology and traditional syngas conversion processes could offer an attractive conversion route for biomass over the long term. Although such concepts received serious attention in the early 1980s, low oil prices made them unattractive. New technology - such as liquid phase methanol production (combined with electricity generation) and new gas separation technology - offers lower production costs and higher overall conversion efficiencies. With large-scale conversion and the production of both fuel and electricity, methanol and hydrogen from lignocellulosic biomass might compete with gasoline and diesel (Spath and others, 2000; Faaij and others, 1999). In addition, synthetic hydrocarbons and methanol can be produced from syngas using Fischer-Tropsch synthesis (Larson and Jin, 1999a, b).

Environmental impacts of biomass energy systems

Biomass energy can be carbon neutral when all biomass produced is used for energy (short carbon cycle). But sustained production on the same surface of land can have considerable negative impacts on soil fertility, water use, agrochemical use, biodiversity, and landscape. Furthermore, the collection and transport of biomass increases the use of vehicles and infrastructure and the emissions to the atmosphere (Tolbert, 1998; Borjesson, 1999; Faaij, Meuleman, and others, 1998). Seen world-wide, climatic, soil, and socioeconomic conditions set strongly variable demands for what biomass production will be sustainable.

Erosion. Erosion is a problem related to the cultivation of many annual crops in many regions. The best-suited energy crops are perennials, with much better land cover than food crops. And during harvest, the removal of soil can be kept to a minimum, since the roots remain in the soil. Another positive effect is that the formation of an extensive root system adds to the organic matter content of the soil. Generally, diseases (such as eelworms) are prevented, and the soil structure is improved.

Water use. Increased water use caused by additional demands of (new) vegetation can become a concern, particularly in arid and semi-arid regions. The choice of crop can have a considerable effect on water-use efficiency. Some eucalyptus species have a very good water-use efficiency, considering the amount of water needed per tonne of biomass produced. But a eucalyptus plantation on a large area could increase the local demand for groundwater and affect its level. On the other hand, improved land cover generally is good for water retention and microclimatic conditions. Thus the impacts on the hydrological situation should be evaluated at the local level.

Agrochemicals. Pesticides affect the quality of groundwater and surface water and thus plants and animals. Specific effects depend on the type of chemical, the quantity used, and the method of application. Experience with perennial crops (willow, poplar, eucalyptus, miscanthus) suggests that they meet strict environmental standards. Compared with food crops like cereals, application rates of agrochemicals per hectare are a fifth to a twentieth for perennial energy crops (Faaij, Meuleman, and others, 1998; Borjesson, 1999).

Nutrients. The abundant use of fertilisers and manure in agriculture has led to considerable environmental problems in various regions: nitrification of groundwater, saturation of soils with phosphate, eutrophication, and unpotable water. Phosphates have also increased the heavy metal flux of the soil. But energy farming with short rotation forestry and perennial grasses requires less fertiliser than conventional agriculture (Kaltschmitt and others, 1996). With perennials, better recycling of nutrients is obtained. The leaching of nitrogen for willow cultivation can be a half to a tenth that for food crops, meeting stringent standards for groundwater protection. The use of plantation biomass will result in removal of nutrients from the soil that have to be replenished in one way or the other. Recycling of ashes is feasible for returning crucial trace elements and phosphates to the soil, already common practice in Austria and Sweden. In Brazil stillage, a nutrient rich remainder of sugar cane fermentation, is returned to sugar cane plantations.

Biodiversity and landscape. Biomass plantations can be criticised because the range of biological species they support is much narrower than what natural forests support (Beyea and others, 1991). Although this is generally true, it is not always relevant. It would be if a virgin forest is replaced by a biomass plantation. But if plantations are established on degraded lands or on excess agricultural lands, the restored lands are likely to support a more diverse ecology.

Degraded lands are plentiful: estimates indicate that about 2 billion hectares of degraded land are 'available' in developing countries (Larson, Williams, and Johansson, 1999; IIASA and WEC, 1998). It would be desirable to restore such land surfaces anyway - for water retention, erosion prevention, and (micro-) climate control. A good plantation design, including areas set aside for native plants and animals fitting in the landscape in a natural way, can avoid the problems normally associated with monocultures, acknowledging that a plantation of energy crops does not always mean a monoculture.

Other risks (fire, disease). Landscaping and managing biomass production systems can considerably reduce the risks of fire and disease. Thus they deserve more attention in coming projects, policies, and research.

Conversion and end use. Conversion of biomass to desired intermediate energy carriers and their use for energy services should meet strict environmental standards as well. Problems that could occur (such as emissions to air) can be easily countered with technology that is well understood and available. Clean combustion of biomass is now common practice in Scandinavia. Gasification allows for cleaning fuel gas prior to combustion or further processing. Care should be paid to small (less than 1 megawatts of thermal energy) conversion systems: technology to meet strict emission standards is available but can have a serious impact on the investment and operational costs of such small systems (Kaltschmitt and others, 1998; Stassen, 1995).

Economics of biomass energy systems

Biomass is a profitable alternative mainly when cheap or even negative-cost biomass residues or wastes are available. To make biomass competitive with fossil fuels, the production of biomass, the conversion technologies, and total bio-energy systems require further optimisation.

TABLE 7.4. MAIN PERFORMANCE DATA FOR SOME CONVERSION ROUTES OF BIOMASS TO FUELS

	RME	Ethanol from sugar or starch crops	Ethanol from lignocellulosic biomass	Hydrogen from lignocellulosic biomass	Methanol from lignocellulosic biomass	Bio-oil from lignocellulos biomass
Concept	Extraction and esterification	Fermentation	Hydrolysis, fermentation, and electricity production	Gasification	Gasification	Flash pyrolysi
Net energy efficiency of conversion	75 percent based onallenergy inputs	50 percent for sugar beet; 44 percent for sugar cane	60 - 70 percent (longer term with power generation included)	55 - 65 percent 60 - 70 percent (longer term)	50 - 60 percent 60 - 70 percent (longer term)	70 percent (raw bio-oil)
Cost range, short	$15 - 25 a gigajoule (northwest Europe)	$15 - 25 a gigajoule for sugar beet; $8 - 10 a	$10 - 15 a gigajoule	$8 - 10 a gigajoule	$11 - 13 a gigajoule	n.a.

term[a]		gigajoule for sugar cane				
Cost range, long term[a]	n.a.	n.a.	$6 - 7 a gigajoule	$6 - 8 a gigajoule	$7 - 10 a gigajoule	Unclear

a. Diesel and gasoline production costs vary widely depending on the oil price. Longer - term projections give estimates of roughly $0.25 - 0.35 a litre, or $8 - 11 a gigajoule. Retail fuel transport prices are usually dominated by taxes of $0.50 - 1.30 a litre depending on the country.

Source: Wyman and others, 1993; IEA, 1994; Williams and others, 1995; Jager and others, 1998; Faaij, Hamelinck, and Agterberg, forthcoming.

Biomass production. Plantation biomass costs already are favourable in some developing countries. Eucalyptus plantations in northeast Brazil supply wood chips at prices between $1.5 - 2.0 a gigajoule (Carpentieri and others, 1993). Costs are (much) higher in industrialised countries, such as $4 a gigajoule in parts of northwest Europe (Rijk, 1994; van den Broek and others, 1997). But by about 2020, with improved crops and production systems, biomass production costs in the United States could be about $1.5 - 2.0 a gigajoule for substantial land surfaces (Graham and others, 1995; Turnure and others, 1995; Hughes and Wiltsee, 1995). It is expected for large areas in the world that low-cost biomass can be produced in large quantities. Its competitiveness will depend on the prices of coal (and natural gas), but also on the costs and net returns from alternative, competing uses of productive land.

Power generation from biomass. With biomass prices of about $2 a gigajoule, state of the art combustion technology at a scale of 40 - 60 megawatts of electricity can result in electricity production costs of $0.05 - 0.06 a kilowatt-hour (USDOE, 1998b; Solantausta

and others, 1996). Co-combustion, particularly at efficient coal-fired power plants, can obtain similar costs. If BIG/CC technology becomes available commercially, production costs could drop further to about $0.04 a kilowatt-hour, especially with higher electrical efficiencies. For larger scales (more than 100 megawatts of electricity) it is expected that cultivated biomass will compete with fossil fuels in many situations. The benefitsoflower specific capital costs and increased efficiency certainly outweigh the increase in costs and energy use for transport for considerable distances if a reasonably well-developed infrastructure is in place (Marrison and Larson, 1995a, b; Faaij, Hamelinck, and Agterberg, forthcoming).

Decentralised power (and heat) production is generally more expensive and therefore is better suited for off-grid applications. The costs of gasifier/diesel systems are still unclear and depend on what emissions and fuel quality are considered acceptable. Combined heat and power generation is generally economically attractive when heat is required with a high load factor.

Production of liquid and gaseous fuels from biomass. The economies of ‘traditional’ fuels like RME and ethanol from starch and sugar cropsin moderate climate zones are poor and unlikely to reach competitive price levels. Methanol, hydrogen, and ethanol from lignocellulosic biomass offer better potential in the longer term (table 7.4).

Implementation issues

Modern use of biomass is important in the energy systems of a number of countries (table 7.5). Other countries can be mentioned as well - as in Asia, where biomass, mainly traditional biomass, can account for 50 - 90 percent of total energy. India has installed more than 2.9 million biomass digesters in villages and produces biogas for cooking - and is using small gasifier diesel systems for rural electrification. Biomass power projects with an aggregate capacity of 222 megawatts have been commissioned in India, with another

280 megawatts under construction (MNCES, 1999). And with tens of millions of hectares of degraded soil, India is involved in wood-for-energy production schemes. Throughout Southeast Asia the interest in modern bio-energy applications has increased in recent years, partly because of the fast-growing demand for power and because biomass residues from various agricultural production systems are plentiful (box 7.2; Lefevre and others, 1997).

TABLE 7.5. BIOMASS IN THE ENERGY SYSTEMS OF SELECTED COUNTRIES

Country	**Role of biomass in the energy system**
Austria	Modern biomass accounts for 11 percent of the national energy supply. Forest residues are used for (district) heating, largely in systems of a relatively small scale.
Brazil	Biomass accounts for about a third of the energy supply. Main modern applications are ethanol for vehicles produced from sugar cane (13 - 14 billion litres a year) and substantial use of charcoal in steel industry. Government supports ethanol. PRO-ALCOOL is moving towards a rationalisation programme to increase efficiency and lower costs.
Denmark	A programme is under way to use 1.2 million tonnes of straw as well as use forest residues. Various concepts have been devised for co-firing biomass in larger-scale combined heating and power plants, district heating, and digestion of biomass residues.
Finland	Twenty percent of its primary energy demand comes from modern biomass. The pulp and paper industry makes a large contribution through efficient residue and black liquor use for energy production. The government supports biomass; a doubling of the contribution is possible with available resources.
Sweden	Modern biomass accounts for 17 percent of national energy demand. Use of residues in the pulp and paper industry and district heating (CHP) and use of wood for space heating are dominant. Biomass is projected to contribute 40 percent to the national energy supply in 2020.
United	About 10,700 megawatts-electric biomass-fired capacity was installed by 1998; largely

States	forest residues. Four billion litres per year of ethanol are produced.
Zimbabwe	Forty million litres of ethanol are produced a year. Biomass satisfies about 75 percent of national energy demand.

Source: Kaltschmitt and others, 1998; Rosillo-Calle and others, 1996; Rosillo and Cortez, 1998; NUTEK, 1996; USDOE, 1998a; Hemstock and Hall, 1995.

Barriers. Bio-energy use varies remarkably among countries. Varying resource potentials and population densities are not the only reasons. Other barriers hamper implementation:

- ***Uncompetitive costs.*** **The main barrier is that the energy carriers are not competitive unless cheap or negative cost biomass wastes and residues are used. Technology development could reduce the costs of bio-energy. In Denmark and Sweden, where carbon and energy taxes have been introduced, more expensive wood fuels and straw are now used on a large scale. But world-wide, the commercial production of energy crops is almost non-existent. (Brazil is a major exception, having introduced subsidies to make ethanol from sugar cane competitive with gasoline.)**

- ***The need for efficient, cheap, environmentally sound energy conversion technologies.*** **Strongly related to costs issues are the availability and the full-scale demonstration of advanced conversion technology, combining a high energy conversion efficiency and environmentally sound performance with low investment costs. Biomass integrated gasifier/combined cycle (BIG/CC) technology can attain higher conversion efficiency at lower costs. Further development of gasification technologies is also important for a cheaper production of methanol and hydrogen from biomass.**

- ***Required development of dedicated fuel supply systems.*** **Experience with**

dedicated fuel supply systems based on 'new' energy crops, such as perennial grasses, is very limited. Higher yields, greater pest resistance, better management techniques, reduced inputs, and further development of machinery are all needed to lower costs and raise productivity. The same is true for harvesting, storage, and logistics.

- ***Specific biomass characteristics.* The solar energy conversion efficiencyof biomass production is low - in practice less than 1 percent. So, fairly large land surfaces are required to produce a substantially amount of energy. Moreover, biomass has a low energy density. Compare coal's energy density of 28 gigajoules a tonne, mineral oil's 42 gigajoules a tonne, and liquefied natural gas's 52 gigajoules a tonne with biomass's 8 gigajoules a tonne of wood (at 50 percent moisture content). Transport is thus an essential element of biomass energy systems, and transportation distances can become a limiting factor. Another complication is that biomass production is usually bound to seasons, challenging the supply and logistics of a total system. And varying weather conditions affect production year-to-year.**

- ***Socioeconomic and organisational barriers.* The production of crops based on perennial grasses or short rotation forestry differs substantially from that of conventional food crops. Annual crops provide farmers with a constant cash flow for each hectare of land. For short rotation coppice, however, the intervals between harvests can be 2 - 10 years, restricting the flexibility of farmers to shift from one crop to another. In addition, bio-energy systems require complex organisations and many actors, creating non-technical barriers.**

- ***Public acceptability.* Since biomass energy systems require substantial land areas if they are to contribute much to the total energy supply, the needed changes in land-use, crops, and landscape might incite public resistance. And to be acceptable**

to most people, the ecological impacts of biomass production systems have to be minimal. Increased traffic in biomass production areas might also be seen as a negative.

- ***Ecological aspects.*** **Not much is known about the effects of large-scale energy farming on landscapes and biodiversity. Energy crop plantations have to fit into the landscape both ecologically and aesthetically. And in addition to minimising the environmental impact, attention should be paid to fitting biomass production into existing agricultural systems.**

- ***Competition for land use.*** **Competition for land or various land claims may turn out to be a limitation in various regions. Opinions differ on how much (agricultural) land will become available for energy crops (Dyson, 1996; Brown and others, 1996; Gardner, 1996). An accepted principle is that biomass production for energy should not conflict with food production. But given the large potential to increase the productivity of conventional agriculture (Luyten, 1995; WRR, 1992; Larson, Williams, and Johansson, 1999), land's availability is not necessarily a barrier. If conventional agriculture has higher productivity, it will become more profitable - so bio-energy will face even stiffer competition from conventional crops than it does today.**

BOX 7.2. INDUSTRIAL USES OF BIO-ENERGY

Two large industrial sectors offer excellent opportunities to use biomass resources efficiently and competitively world-wide: paper and pulp, and sugar (particularly using sugar cane as feed). Traditionally, these sectors use biomass residues (wood waste and bagasse) for their internal energy needs, usually inefficient conversions to low-pressure steam and some power. The absence of regulations to ensure reasonable electricity tariffs for independent power producers make it unattractive for industries to invest in more efficient power generation. But the liberalisation of energy markets in many countries is removing this barrier, opening a window to reduce production costs and modernise production capacity.

Efficient boilers have been installed in many production facilities. Gasification technology could offer even further efficiency gains and lower costs - say, when applied for converting black liquor (Larson and others, 1998). The power generated is generally competitive with grid prices. In Nicaragua electricity production from bagasse using improved boilers could meet the national demand for electricity (van den Broek and van Wijk, 1998).

Some 700-1,400 million hectares may be available for biomass energy production well into the 21st century.

Strategies. Six areas are essential for successful development and implementation of sustainable and economically competitive bio-energy systems: technologies, production, markets, polygeneration, externalities, and policy.

Technological development and demonstration of key conversion technologies. **Research, demonstration, and commercialisation of advanced power generation technology are essential - especially for BIG/CC technology, which can offer high conversion efficiencies, low emissions, and low costs. Another interesting route is producing modern biofuels, using hydrolysis and gasification. Combining biomass with fossil fuels can be an excellent way to achieve economies of scale and reduce the risks of supply disruptions.**

More experience with and improvement of biomass production. **Local assessments are needed to identify optimal biomass production systems, and more practical experience is needed with a wide variety of systems and crops. Certainly, more research and testing are**

needed to monitor the impact of energy crops, with particular attention to water use, pest abatement, nutrient leaching, soil quality, biodiversity (on various levels), and proper landscaping. Perennial crops (grasses) and short rotation coppice (eucalyptus, willow) can be applied with minimal ecological impacts.

Cost reduction is essential, though several countries already obtain biomass production costs below $2 a gigajoule. Larger plantations, improved species, and better production systems and equipment can reduce costs further. Another promising way to lower costs is to combine biomass production for energy with other (agricultural or forest) products (multi-output production systems). Yet another is to seek other benefits from biomass production - preventing erosion, removing soil contaminants, and creating recreational and buffer zones.

Creating markets for biomass production, trade, and use. **At local and regional scales, the starting phase of getting bio-energy ‘off the ground’ can be difficult. The supply and demand for biomass need to be matched over prolonged periods. Diversifying biomass supplies can be a key in creating a better biomass market. Flexible conversion capacity to deal with different biomass streams, as well as fossil fuels, is also important. And international trade in bio-energy can buffer supply fluctuations.**

Production can also be started in niches. Major examples are the modernisation of power generation in the sugar, in paper and pulp, and in (organic) waste treatment. Regulations - such as acceptable payback tariffs for independent power producers - are essential. Niche markets can also be found for modern biofuels, such as high-value fuel additives, as mixes with gasoline, or for specific parts of a local transport fleet (such as buses). Successful biomass markets are working in Scandinavian countries and in Brazil (boxes 7.3 and 7.4).

Polygeneration of products and energy carriers. **To compete with coal (chapter 8),**

biomass energy may have to follow a polygeneration strategy - coproducing electricity, fuels, fibres, and food from biomass. One example would be the generation of electricity by a BIG/CC plant as well as any fluid that can be produced from the syngas: methanol, dimethyl ether (DME), other liquids using Fischer-Tropps synthesis (Larson and Jin, 1999a; Faaij and others, 1999). Another could combine biomass and fossil fuels to coproduce modern energy carriers (Oonk and others, 1997).

BOX 7.3. BRAZIL'S NATIONAL ALCOHOL PROGRAMME

PRO-ALCOOL in Brazil is the largest programme of commercial biomass utilisation in the world. Despite economic difficulties during some of its 25 years of operation, it presents several environmental benefits, reduces import expenditures, and creates jobs in rural areas.

Roughly 700,000 rural jobs in sugar-alcohol are distributed among 350 private industrial units and 50,000 private sugarcane growers. Moreover, the cost of creating a job in sugar-alcohol is much lower than in other industries. But mechanical harvesting could change this.

Despite a small reduction in harvested surface, Brazilian sugar-cane production has shown a continuous increase, reaching 313 million tonnes in the 1998/99 season. Alcohol consumption has been steady, even though almost no new hydrated ethanol powered automobiles are being produced. The decline in consumption from the partial age retirement of this fleet has been balanced by significant growth in the number of automobiles using a blend of 26 percent anhydrous ethanol in gasoline.

Subsidies were reduced in recent years in the southeast of Brazil, where 80 percent of the ethanol is produced, and then fully removed early in 1999. Some government actions - compulsory increases in the amount of ethanol blended in gasoline and special financial conditions for acquisition of new hydrated ethanol powered cars - have favoured producers. Very recently the alcohol price at the pump stations was reduced, triggering the interest of consumers and carmakers in hydrated ethanol cars. Other government policies may include tax reductions on new alcohol cars, ‘green’ fleets, and mixing alcohol-diesel for diesel motors.

Another promising option is the implementation of a large cogeneration programme for sugar and alcohol. Revenues from electricity sales could allow further reductions in the cost of alcohol production, although it is not yet enough to make it competitive with gasoline in a free market. Even so, production costs continue to come down from learning by doing.

The programme has positive environmental and economic impacts. In 1999 it resulted in an emission reduction of almost 13 mega-tonnes of carbon. And the hard currency saved by not importing oil totals $40 billion over the 25 years since alcohol’s introduction.

BOX 7.4. BIOMASS USE IN SWEDEN

Sweden is probably the world leader in creating a working biomass market. Its use of biomass for energy purposes - domestic heating with advanced heating systems, district heating, and combined heat and power generation - has increased 4 - 5-fold in the past 10 years. And the average costs of biomass have come down considerably. Swedish forests have met this growing demand with ease.

The growing contribution of biomass has been combined with a big increase in the number of companies supplying wood and wood products and in the number of parties using biomass. As a result competition has led to lower prices, combined with innovation and more efficient biomass supply systems.

Some 14,000 hectares in short rotation willow plantations have been established. Sweden also imports some biomass, which make up only a small part of the total supply but keep prices low.

Sweden plans to increase the 20 percent share of biomass in the total primary energy supply to 40 percent in 2020, largely by extending and improving the use of residues from production forests and wood processing industries (NUTEK, 1996).

Internalising external costs and benefits. **Bio-energy can offer benefits over fossil fuels that do not show up in its cost - that is, it can offer externalities. Being carbon-neutral is one. Another is the very low sulphur content. A third is that biomass is available in most countries, while fossil fuels often need to be imported. The domestic production of bio-energy also brings macro-economic and employment benefits (Faaij, Meuleman, and others, 1998). It can offer large numbers of unskilled jobs (van den Broek and van Wijk, 1998). It has fewer external costs than (imported) coal and oil (Borjesson, 1999; Faaij, Meuleman, and others, 1998).**

Policies. **Carbon taxes, price supports, and long-running research and development (R&D) programmes are often central in gaining experience, building infrastructure developing technology, and fostering the national market. Scandinavia and Brazil - and to a somewhat less extent northwest Europe and the United States - show that modernisation is essential for realising the promise of biomass as an alternative energy source (Ravindranath and Hall, 1995). It may even help in phasing out agricultural subsidies.**

Conclusion

- **Biomass can make a large contribution to the future world's energy supply. Land for biomass production should not be a bottleneck, if the modernisation of conventional agricultural production continues. Recent evaluations indicate that if land surfaces of 400 - 700 million hectares were used for biomass energy production halfway into the 21st century, there could be no conflicts with other land-use functions and the preservation of nature.**

- **Bio-energy's current contribution of 45 ± 10 exajoules a year - of which probably 16 ± 6 exajoules a year is commercial - could increase to 100 - 300 exajoules a year in the 21st century.**

- **The primary use of biomass for modern production of energy carriers accounts for about 7 exajoules a year. Modern biomass energy production can play an important role in rural development.**

- **Although developing countries are the main consumers of biomass, the potential, production, and use of biomass in these countries are often poorly quantified and documented.**

- **Biomass can be used for energy production in many forms. The resource use, the technologies applied, and the set-up of systems will depend on local conditions, both physical and socioeconomic. Perennial crops offer cheap and productive biomass production, with low or even positive environmental impacts.**

- **Production costs of biomass can be $1.5 - 2 a gigajoule in many regions. Genetic improvement and optimised production systems - and multi-output production systems, cascading biomass, and multifunctional land use - could bring bio-mass close to the (expected) costs of coal.**

- **A key issue for bio-energy is mod-ernising it to fit sustainable development. Conversion of biomass to modern energy carriers (electricity, fuels) gives biomass commercial value that can provide income and development for local (rural) economies.**

- **Modernised biomass use can be a full-scale player in the portfolio of energy options for the longer term. The production of electricity and fuels from lignocellulosic biomass are promising options. But they require the development of markets, infrastructure, key conversion technologies (BIG/CC), and advanced fuel production systems.**

- **Flexible energy systems combining biomass and fossil fuels are likely to become**

the backbone for low-risk, low-cost energy supply systems.

An accepted principle is that biomass production for energy should not conflict with food production.

Wind energy

Wind energy, in common with other renewable energy sources, is broadly available but diffuse. The global wind resource has been described in chapter 5. Wind energy was widely used as a source of power before the industrial revolution, but later displaced by fossil fuel use because of differences in costs and reliability. The oil crises of the 1970s, however, triggered renewed interest in wind energy technology for grid-connected electricity production, water pumping, and power supply in remote areas (WEC, 1994b).

In recent decades enormous progress has been made in the development of wind turbines for electricity production. Around 1980 the first modern grid-connected wind turbines were installed. In 1990 about 2,000 megawatts of grid-connected wind power was in operation world-wide - at the beginning of 2000, about 13,500 megawatts. In addition, more than 1 million water-pumping wind turbines (wind pumps), manufactured in many developing countries, supply water for livestock, mainly in remote areas. And tens of thousands of small battery-charging wind generators are operated in China, Mongolia, and Central Asia (chapter 10).

The potential of wind energy

The technical potential of onshore wind energy to fulfil energy needs is very large - 20,000

- 50,000 terawatt-hours a year (chapter 5). The economic potential of wind energy depends on the economics of wind turbine systems and of alternative options. Apart from investment costs, the most important parameter determining the economics of a wind turbine system is annual energy output, in turn determined by such parameters as average wind speed, statistical wind speed distribution, turbulence intensities, and roughness of the surrounding terrain. The power in wind is proportional to the third power of the momentary wind speed.

Because of the sensitivity to wind speed, determining the potential of wind energy at a specific site is not straightforward. More accurate meteorological measurements and wind energy maps and handbooks are being produced and (mostly) published, enabling wind project developers to better assess the long-term economic performance of their projects.

In densely populated countries the best sites on land are occupied, and public resistance makes it difficult to realise new projects at acceptable cost. That is why Denmark and the Netherlands are developing offshore projects, despite less favourable economics. Sweden and the United Kingdom are developing offshore projects to preserve the landscape.

Resources offshore are much larger than those onshore, but to be interesting they have to be close to electric infrastructure. A comprehensive study by Germanische Lloyd and Garrad Hassan & Partners (Matthies and others, 1995) concluded that around 3,000 terawatt-hours a year of electricity could be generated in the coastal areas of the European Union (excluding Finland and Sweden). With electricity consumption in those 12 countries at about 2,000 terawatt-hours a year, offshore options should be included in assessments of the potential of wind electricity.

Development of installed wind power

In 1997 the installed wind power was about 7,400 megawatts, in 1998 close to 10,000 megawatts, and in 1999 another annual 3,600 megawatts was installed (BTM Consult,

1999 and 2000). Between 1994 and 1999 the annual growth of installed operating capacity varied between 27 and 33 percent. The electricity generated by wind turbines can be estimated at 18 terawatt-hours in 1998 and 24 terawatt-hours in 1999.

There are 29 countries that have active wind energy programmes. Most of the capacity added in 1998 (2,048 megawatts) was in four countries: for Germany 793 megawatts, for the United States 577 megawatts, for Spain 368 megawatts, and for Denmark 310 megawatts (table 7.6).

Based on an analysis of the national energy policies for the most relevant countries, BMT Consult expects the global installed power to grow to around 30,000 megawatts of electricity in 2004.

Several generic scenarios assess the growth of wind power in the coming decades. One of the most interesting - by BTM Consult for the FORUM for Energy & Development, presented at the COP-4 of the UN-FCCC in Buenos Aires in December 1998 - addresses three questions. Can wind power contribute 10 percent of the world's electricity needs within three decades? How long will it take to achieve this? How will wind power be distributed over the world?

Two scenarios were developed. The *recent trends* scenario extrapolates current market development, while the *international agreements* scenario assumes that international agreements are realised. Both scenarios assumed that integrating up to 20 percent of wind power in the grid (in energy terms) would not be a problem with present grids, modern fossil fuel power plants, and modern wind turbines. Analysis of the world's exploitable wind resources, with growth of electricity demand as indicated in the *World Energy Outlook* (IEA, 1995 and 1996), led to the following conclusions:

- **Under the recent trends scenario - starting with 20,000 megawatts by the end of 2002 and assuming a 15 percent cost reduction, and later 12 percent and 10** percent, for each doubling of the accumulated number of installations - 10 percent penetration is achieved around 2025, and saturation in 2030 - 35, at about 1.1 terawatt. In this scenario the cost of generating wind electricity would come down to $0.032 a kilowatt-hour (1998 level) on average, ± 15 percent (depending on wind speed, connection costs to the grid, and other considerations).

- Under the international agreements scenario - with the same starting conditions but a slightly different learning curve - growth is faster and 10 percent penetration is achieved around 2016, with saturation in 2030 - 35 at about 1.9 terawatts. In this scenario the cost would come down to $0.027 a kilowatt-hour on average, again ± 15 percent.

TABLE 7.6. INSTALLED WIND POWER, 1997 AND 1998

	Installed megawatts 1997	Cumulative megawatts 1997	Installed megawatts 1998	Cumulative megawatts 1998
Canada	4	26	57	83
Mexico	0	2	0	2
United States	29	1.611	577	2.141
Latin America	10	42	24	66
Total Americas	**43**	**1.681**	**658**	**2.292**
Denmark	285	1.116	310	1.420
Finland	5	12	6	18
France	8	13	8	21
Germany	533	2.081	793	2.874
Greece	0	29	26	55

Ireland	42	53	11	64
Italy	33	103	94	197
Netherlands	44	329	50	379
Portugal	20	39	13	51
Spain	262	512	368	880
Sweden	19	122	54	176
United Kingdom	55	328	10	338
Other Europe	13	57	23	80
Total Europe	**1.318**	**4.793**	**1.766**	**6.553**
China	67	146	54	200
India	65	940	52	992
Other Asia	9	22	11	33
Total Asia	**141**	**1.108**	**117**	**1.224**
Australia and New Zealand	2	8	26	34
Pacific Islands	0	3	0	3
North Africa (incl. Egypt)	0	9	0	9
Middle East	8	18	0	18
Former Soviet Union	1	19	11	19
Total other continents and areas	**11**	**57**	**37**	**83**
Annual installed capacity worldwide	**1.513**		**2.577**	
Cumulative capacity		**7.639**		**10.153**

installed worldwide				

Note: The cumulative installed capacity by the end of 1998 is not always equal to the 1997 data plus installed capacity during 1998, because of adjustments for decommissioned and dismantled capacity.

Source: BTM Consult, 1999.

In this second scenario, the regional distribution of wind power is North America 23 percent, Latin America 6 percent, Europe (Eastern and Western) 14 percent, Asia 23 percent, Pacific OECD 8 percent, North Africa 5 percent, former Soviet Union 16 percent, and rest of the world 5 percent.

Technology developments

Wind turbines become larger. From the beginning of the modern wind energy technology era in the mid-1970s, there has been gradual growth in the unit size of commercial machines. In the mid-1970s the typical size of a wind turbine was 30 kilowatts of generating capacity, with a rotor diameter of 10 metres. The largest units installed in 1998 had capacities of 1,650 kilowatts with rotor diameters of 66 metres. By 1999, 460 units with a generating capacity of 1 megawatt or more were installed world-wide. Turbines with an installed power of 2 megawatts (70 metres diameter) are being introduced in the market, and 3 - 5 megawatt machines are on the drawing board (table 7.7).

Market demands drive the trend towards larger machines: economies of scale, less visual impacts on the landscape per unit of installed power, and expectations that offshore potential will soon be developed. The average size of wind turbines installed is expected to be 1,200 kilowatts before 2005 and 1,500 kilowatts thereafter. Note, however, that the optimum size of a turbine - in cost, impact, and public acceptance - differs for onshore

(nearby as well as remote) and offshore applications.

Wind turbines become more controllable and grid-compatible. The output of stall regulated wind turbines is hardly controllable, apart from switching the machine on and off. Output varies with the wind speed until reaching the rated wind speed value. As the application of the aerodynamic stall phenomena to structural compliant machines gets more difficult with bigger turbines, blade pitch control systems are being applied to them. For structural dynamics and reliability, a blade-pitch system should be combined with a variable speed electric conversion system. Such systems typically incorporate synchronous generators combined with electronic AC-DC-AC converters.

TABLE 7.7. AVERAGE SIZE OF INSTALLED WIND TURBINES, 1992 - 99

Year	**Size (kilowatts)**
1992	200
1994	300
1996	500
1998	600
1999	700

Modern electronic components have enabled designers to control output - within the operational envelope of the wind speed - and produce excellent power quality. These developments make wind turbines more suitable for integration with the electricity infrastructure and ultimately for higher penetration. These advantages are of particular interest for weak grids, often in rural and remote areas that have a lot of wind.

Wind turbines will have fewer components. For lower costs and greater reliability and

maintainability, designers now seek technology with fewer components - such as directly driven, slow-running generators, with passive yaw and passive blade pitch control. In Germany 34 percent of the installed power in 1998 (770 megawatts) was realised with this type of technology.

Special offshore designs are on the drawing board. With the first offshore wind farms in Europe, industrial designers are developing dedicated turbine technologies for large wind farms in the open sea (Beurskens, 2000). Outages onshore can often be corrected quickly so that only a small amount of energy is lost. But offshore the window for carrying out repairs or replacing components is often limited. The high cost of complete installations implies the use of large wind turbines, which will probably have installed powers of 3 - 6 megawatts. Offshore design features will include novel installation concepts, electricity conversion and transport systems, corrosion protection, and integration with external conditions (both wind and wave loading).

Time to market is becoming shorter than project preparation time. Although there is a temporary shortage of supply of wind turbines in some countries, competition among manufacturers is fierce. One way to become more competitive is to keep implementing innovations and component improvements to reduce cost. Times to market new products are also becoming short (two to three years). As a result, just as the construction of a wind farm commences, the technology is already outdated.

System aspects

Wind turbines deliver energy, but little capacity. Because wind energy is intermittent, wind turbines mainly deliver energy, but little capacity value often 20 percent or less of the installed wind power. And this percentage falls when the penetration of wind turbines increases, requiring even more back-up power for a reliable energy supply. But wind-generated electricity can be transformed from intermittent to baseload power if it is

combined with, say, compressed air energy storage. In this way a high capacity factor can be achieved with a small economic penalty, potentially about $0.01 a kilowatt-hour (Cavallo, 1995). This option becomes attractive when wind electricity generation costs fall below $0.03 a kilowatt-hour. It also opens the possibility of exploiting wind resources remote from markets, as in the Great Plains of the United States (Cavallo, 1995) and in inner Mongolia and northwest China (Lew and others, 1998).

Wind power becomes more predictable. Meteorological research on predicting the output of wind farms a few hours in advance has produced computer programs that optimise the operational and fuel costs of regional electricity production parks (Denmark, Germany). This will increase the capacity value of wind power and the value of the electricity produced.

Capacity factors are somewhat adjustable. Some general misconceptions sometimes lead to the wrong decisions or conclusions. The capacity factor (annual energy output/output based on full-time operation at rated power) depends on local winds and wind turbines. By optimising the turbine characteristics to the local wind regime, the capacity factor - now often 20 - 25 percent - can be optimised without losing too much energy output. But extreme capacity factors - say, 40 percent - automatically means a large loss of potential energy output.

Renewed interest in autonomous systems. In the mid-1980s interest grew in the application of wind turbines in isolated areas without an energy infrastructure. Two systems can be distinguished:

- **Hybrid systems, in which a wind turbine operates in parallel with, for example, a diesel set (to save fuel consumption and to decrease maintenance and repairs) or a diesel generator combined with a battery storage unit.**

- **Standalone units, for charging batteries, pumping water for irrigation, domestic**

use, watering cattle, or desalination and cooling.

More than 30 experimental hybrid systems have been developed and tested, almost all stopped without a commercial follow up, because of unreliable and expensive components. The interest in hybrid and standalone systems is being revived - initiated by the search for new markets for renewable energy systems and influenced by spectacular improvements in performance and cost for wind turbines and power electronics (box 7.5 and chapter 10). For successful market entry, systems have to be modular, and standards for components and subsystems introduced.

Small battery-charging wind generators are manufactured by the thousand in China, Mongolia, and elsewhere, making them more numerous than larger diameter wind generators. Although their contribution to world energy supply is negligible, their potential impact on the energy needs of rural and nomadic families is significant (as with photovoltaic home systems).

Environmental aspects

Environmental aspects come into play in the three phases of a wind turbine project: building and manufacturing, normal operation during the turbine's lifetime, decommissioning

> Industrial designers are developing dedicated turbine technologies for large wind farms in the open sea.

Building and manufacturing. No exotic materials or manufacturing processes are required

in producing a wind turbine or building the civil works. The energy payback time of a large wind turbine, under typical Danish conditions, is 3 to 4 months (Dannemand Andersen, 1998).

Normal operation. Negative environmental aspects connected to the use of wind turbines are: acoustic noise emission, visual impact on the landscape, impact on bird life, moving shadows caused by the rotor, and electromagnetic interference with radio, television, and radar signals. In practice the noise and visual impact cause the most problems. Acoustic noise emission prevents designers from increasing the tip speed of rotor blades, which would increase the rotational speed of the drive train shaft and thus reduce the cost of gearboxes or generators. Aero-acoustic research has provided design tools and blade configurations to make blades considerably more silent, reducing the distance needed between wind turbines and houses.

The impact on bird life appears to be minor if the turbines are properly located. A research project in the Netherlands showed that the bird casualties from collisions with rotating rotor blades on a wind farm of 1,000 megawatts is a very small fraction of those from hunting, high voltage lines, and vehicle traffic (Winkelman, 1992). In addition, acoustic devices might help prevent birds from flying into rotor blades (Davis, 1995).

During normal operation a wind turbine causes no emissions, so the potential to reduce carbon dioxide emissions depends on the fuel mix of the fossil-fuelled plants the wind turbine is working with. A study by BTM Consult (1999) indicates that in 2025 wind energy could prevent the emission of 1.4 - 2.5 gigatonnes of carbon dioxide a year.

Decommissioning. Because all components are conventional, the recycling methods for decommissioning the wind turbine are also conventional. Most blades are made from glass or carbon fibre reinforced plastics, processed by incineration. To replace glass and carbon and close the cycle of material use, wood composites are being applied and biofibres

developed.

BOX 7.5. HYBRID WIND, BATTERY, AND DIESEL SYSTEMS IN CHINA

Since 1994 the 360 inhabitants of the village of Bayinaobao in Inner Mongolia have been provided with electricity from a hybrid electricity system that employs two 5-kilowatt wind turbines, a battery storage unit, and a diesel generator. In this system the wind turbines provide about 80 percent of the electricity generated. The technology is being developed under a German-Chinese industrial joint venture aimed at transferring the German-developed wind turbine and ancillary technologies. By the time 140 systems have been built, local content should account for about 70 percent of the wind turbine technology, reducing the cost of an imported system by half. Based on the performance of the first unit and the costs projected for components, the electricity from the hybrid system will cost less (up to 22 percent less, at a diesel fuel price of $0.38 a litre) than from the conventional diesel system (Weise and others, 1995).

Economic aspects

The energy generation costs of wind turbines are basically determined by five parameters:

- ***Turnkey project cost.*** **Initial investment costs (expressed in U.S. dollars a square metre of swept rotor area), project preparation, and infrastructure make up the turnkey project costs. The costs of European wind turbines are typically $410 a square metre (machine cost, excluding foundation). Project preparation and infrastructure costs depend heavily on local circumstances, such as soil conditions, road conditions, and the availability of electrical substations. Turnkey costs vary from $460 a square metre to $660 a square metre (with 1 ECU = 1.1 U.S. dollar).**

- ***Energy output of the system.*** **The energy output of a wind turbine can be estimated by E = *b*. V^3 kilowatt-hours a square metre, where E is the annual energy**

output, *b* is the performance factor, and V is the average wind speed at hub height. The factor *b* depends on the system efficiency of the wind turbine and the statistical distribution of wind speeds. In coastal climates in Europe a value of 3.15 for *b* is representative for modern wind turbines and not too far away from the theoretical maximum. On good locations in Denmark, northern Germany, and the Netherlands annual outputs of more than 1,000 kilowatt-hours a square metre are often achieved.

• *Local average wind speed.* In general, local average wind speed should exceed five metres a second at a height of 10 metres to allow economic exploitation of grid-connected wind turbines. *Availability of the system.* The technical availability of modern wind farms exceeds 96 percent.

• *Lifetime of the system.* Design tools have improved so much that designing on the basis of fatigue lifetime has become possible. As a result one can confidently use lifetimes of 15 - 20 years for economic calculations.

FIGURE 7.2. DEVELOPMENT OF WIND ELECTRICITY GENERATION COSTS IN DENMARK, 1981 - 1997

Source: BTM Consult, 1999.

For Europe a state-of-the-art reference calculation uses the following values:

Turnkey cost	$600 a square metre
Interest	5 percent
Economic lifetime	15 years
Technical availability	95 percent
Annual energy output	3.15 V^3 kilowatt-hours a square metre
O & M costs	$0.005 a kilowatt-hour

If average wind speeds at the hub height range from 5.6 - 7.5 metres a second, the corresponding electricity production cost is $0.12 - 0.05 a kilowatt-hour. Because the energy of the wind is proportional to the third power of the wind speed, the economic calculations are very sensitive to the local average annual wind speed.

Figure 7.2 illustrates the cost reductions for electricity generation from wind turbines in Denmark since 1981. But take care in translating these figures to other regions, for the cost of project preparation, infrastructure, and civil works in Denmark is low relative to many other regions. BTM Consult (1999) expects a 35 - 45 percent reduction in generation costs in the next 15 - 20 years (figure 7.3).

Implementation issues

Manufacturers and project developers usually identify the following items as serious barriers for efficient implementation of wind turbine projects:

- **Fluctuating demand for wind turbines as a result of changing national policies and support schemes.**
- **Uncertainties leading to financing costs as a result of changing governmental**

policies.

- **Complicated, time-consuming, and expensive institutional procedures, resulting from a lack of public acceptance, which varies consid-erablyfrom country to country.**

- **Project preparation time often longer than the ‘time to market’ of new wind turbine types.**

- **Lack of sufficient international acceptance of certification procedures and standards.**

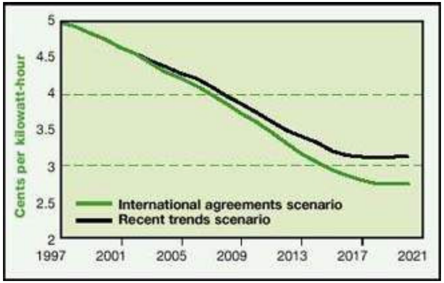

FIGURE 7.3. POTENTIAL COST REDUCTIONS FOR WIND POWER, 1997 - 2020

Source: BTM Consult, 1999.

Denmark and the United States were the first to introduce an integrated approach to wind energy, encompassing both technical development and the introduction of market incentives. Now more than 25 countries use a great variety of incentives, some very successful and some complete failures. The applied incentive schemes can be grouped in three categories, or in combinations of these categories:

- **Fixed tariff systems, such as those of Denmark, Germany, and Spain (favourable payback tariffs are fixed for a period of, say, 10 years).**

- **Quota or concession systems, such as the Non Fossil Fuel Obligation of England and the systems of France, Ireland, and Scotland (competitive bidding for projects until a set amount of electricity production is realised).**

- **Other systems to stimulate the application of wind energy, such as tax breaks, carbon taxes, green electricity, and tradable green labels.**

With the first schemes, Denmark, Germany, and Spain installed many more wind turbines than countries using other schemes. Elsewhere in Europe, the second system has demonstrated success also (table 7.8). But none of the schemes can be easily translated from one country to another. Legal circumstances and public acceptance may differ completely. Moreover, several incentives have been introduced only recently, and their effectiveness is not yet known.

Under favourable legislation and general acceptance by the public, a fixed tariff system may be quite successful, because it provides financial security to project developers, owners, and financiers. In the long term, however, fixed tariffs will become too expensive to subsidise if they are not modified. As a result the industry might collapse unless the incentive program brings the cost of the technology down. Quota systems based on calls for tenders only once in two or three years may lead to extreme fluctuations in the market growth. Concessions appear interesting for harnessing large, high-quality wind resources in regions remote from major electricity markets (PCAST, 1999). However, very large wind projects for remote wind resources require a different industry structure from today’s. Needed are large project developers with deep financial pockets - not wind turbine suppliers. The installation of wind turbines can also increase if individuals, groups of individuals, or cooperatives are allowed to own one or more wind turbines as small

independent power producers (IPPs) and to sell electricity to the grid.

It is too early to judge whether tradable green certificates, connected to a quota system, are viable. Marketing green electricity seems to developsuccessfully only when the public recognises green electricity as a product different from regular electricity, worth the additional costs.

TABLE 7.8. TYPE OF INCENTIVE AND WIND POWER ADDED IN 1998

Type of incentive	Country	Megawatts added	Percentage increase
Fixed tariffs	Denmark	310	28
	Germany	793	38
	Spain	368	72
	Total	**1,471**	**40**
Quota or concession systems	France	8	62
	Ireland	11	21
	United Kingdom	10	3
	Total	**29**	**7**

Conclusion

- **The potential of wind energy is large, with the technical potential of generating electricity onshore estimated at 20,000 - 50,000 terawatt-hours a year.**

- **When investigating the potential, special attention should go to possibilities offshore. Studies for Europe indicate that the offshore wind resources that can be tapped are bigger than the total electricity demand in Europe.**

- **The average growth rate of the cumulative capacity over the last six years has been about 30 percent a year, bringing the cumulative installed wind turbine capacity to about 10,000 megawatts at the end of 1998 and about 13,500 megawatts at the end of 1999 - and wind energy production to 18 terawatt-hours in 1998 and 24 terawatt-hours in 1999.**

- **Wind turbines are becoming larger, with the average size installed in 1998 at 600 kilowatts, up from about 30 kilowatts in the mid-1970s. Turbines of megawatt size are being developed and should soon be commercially available.**

- **Costs have to come down further, requiring development of advanced flexible concepts and dedicated offshore wind energy systems. Cost reductions up to 45 percent are feasible within 15 years. Ultimately wind electricity costs might come down to about $0.03 a kilowatt-hour.**

- **Although wind-generated electricity is an intermittent resource, it can be transformed to baseload power supply if combined with energy storage. For compressed air energy storage the additional costs may be limited to about $0.01 a kilowatt-hour, opening the possibility of exploiting good wind resources remote from markets.**

- **The environmental impacts of wind turbines are limited, with noise and visibility causing the most problems, increasing public resistance against the installation of new turbines in densely populated countries.**

- **Interest in small turbines is being revived for standalone and autonomous systems in rural areas.**

Photovoltaic solar energy

Photovoltaic solar energy conversion is the direct conversion of sunlight into electricity. This can be done by flat plate and concentrator systems.

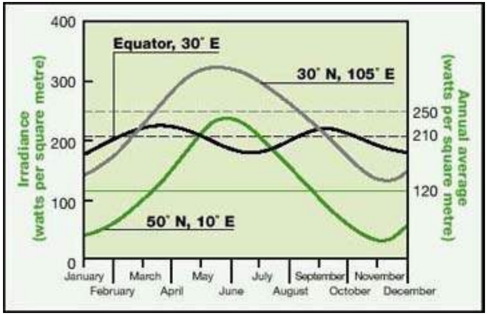

FIGURE 7.4. VARIATIONS IN AVERAGE MONTHLY INSOLATION OVER THE YEAR IN THREE LOCATIONS

Source: Eliasson, 1998.

TABLE 7.9. POTENTIAL CONTRIBUTION OF SOLAR ENERGY TECHNOLOGIES TO WORLD ENERGY CONSUMPTION ACCORDING TO DIFFERENT STUDIES (EXAJOULES OF ELECTRICITY)

Study	2020 - 2025	2050	2100
WEC, 1994 a,b	16		
IIASA and WEC, 1998	2 - 4	7 - 14	
RIGES, 1993 (solar and wind)	17	35	
Shell, 1996	<10	200	
Greenpeace and SEI, 1993(solar and wind)	90	270	830

Reference: total world energy consumption	400 - 600	400 - 1,200	

An essential component of these systems is the solar cell, in which the photovoltaic effect - the generation of free electrons using the energy of light particles - takes place. These electrons are used to generate electricity.

Characteristics of the source

Solar radiation is available at any location on the surface of the Earth. The maximum irradiance (power density) of sunlight on Earth is about 1,000 watts a square metre, irrespective of location. It is common to describe the solar source in terms of insolation - the energy available per unit of area and per unit of time (such as kilowatt-hours per square metre a year). Measured in a horizontal plane, annual insolation varies over the Earth’s surface by a factor of 3 - from roughly 800 kilowatt-hours per square metre a year in northern Scandinavia and Canada to a maximum of 2,500 kilowatt-hours per square metre a year in some dry desert areas.

The differences in average monthly insolation (June to December) can vary from 25 percent close to the equator to a factor of 10 in very northern and southern areas (figure 7.4), determining the annual production pattern of solar energy systems. The ratio of diffuse to total annual insolation can range from 10 percent for bright sunny areas to 60 percent or more for areas with a moderate climate, such as Western Europe. The actual ratio largely determines the type of solar energy technology that can be used (non-concentrating or concentrating).

The potential of photovoltaic solar energy

The average power density of solar radiation is 100 - 300 watts a square metre. The net conversion efficiency of solar electric power systems (sunlight to electricity) is typically 10 - 15 percent. So substantial areas are required to capture and convert significant

amounts of solar energy to fulfil energy needs (especially in industrialised countries, relative to today’s energy consumption). For instance, at a plant efficiency of 10 percent, an area of 3 - 10 square kilometres is required to generate an average of 100 megawatts of electricity - 0.9 terawatt-hours of electricity or 3.2 petajoules of electricity a year - using a photovoltaic (or solar thermal electricity) system.

The total average power available at the Earth’s surface in the form of solar radiation exceeds the total human power consumption by roughly a factor of 1,500. Calculated per person, the average solar power available is 3 megawatts, while the consumption varies from 100 watts (least industrialised countries) to 10 kilowatts (United States), with an average of 2 kilowatts. Although these numbers provide a useful rough picture of the absolute boundaries of the possibilities of solar energy, they have little significance for the technical and economic potential. Because of differences in the solar energy supply pattern, energy infrastructure, population density, geographic conditions, and the like, a detailed analysis of the technical and economic potential of solar energy is best made regionally or nationally. The global potential is then the sum of these national or regional potentials.

The *economic* potential of solar energy, a matter of debate, depends on the perspectives for cost reduction. In the recent past several scenario studies have assessed the potential application of solar energy technologies (IIASA and WEC, 1998; WEC, 1994a,b; Johansson and others, 1993a; Shell, 1996; Greenpeace and SEI, 1993). They provide a picture of different views on the potential penetration of solar energy in the 21st century (table 7.9).

The *technical* potential of photovoltaics has been studied in some detail in several countries. In densely populated countries with a well-developed infrastructure, there is an emphasis on applications of grid-connected photovoltaic systems in the built environment (including infrastructural objects like railways and roads). These systems are necessarily small- or medium-sized, typically 1 kilowatt to 1 megawatt.[1] The electricity is generated

physically close to the place where electricity is also consumed. In less densely populated countries there is also considerable interest in ‘ground-based’ systems, generally larger than 1 megawatt. The area that would be required to generate an average electrical power equal to the total present human power consumption - assuming 10 percent plant efficiency and an insolation of 2,000 kilowatt-hours per square metre a year - is roughly 750 x 750 square kilometres. In countries or rural regions with a weak or incomplete grid infrastructure, small standalone systems and modular electric systems may be used for electrification of houses or village communities.

Photovoltaic market developments

Between 1983 and 1999 photovoltaic shipments grew by just over 15 percent a year (figure 7.5). In 1998 around 150 megawatts of solar cell modules were produced, in 1999 nearly 200 megawatts. In 1998 cumulative production was around 800 megawatts. Probably about 500 megawatts, perhaps 600 megawatts, of this production was in operation in 1998, generating about 0.5 terawatt-hours a year. In 1993 - 98 operating capacity increased by roughly 30 percent a year.

In 1990 - 94 the market share of solar home systems and village power systems was 20 percent (based on power volume). Grid-connected systems accounted for 11 percent, with the rest for water pumping, communication, leisure, consumer products, and the like (EPIA and Altener, 1996). In 1995 - 98 the relative importance of grid-connected systems increased to 23 percent (Maycock, 1998).

Current status and future development of photovoltaic solar cells and modules

The major component of photovoltaic solar energy systems is the solar module, normally a number of solar cells connected in series. The efficiency of an ideal photovoltaic cell is about 30 percent at most (for a single cell under natural sunlight). Higher efficiencies can be achieved by stacking cells with different optical properties in a tandem device, by using

concentrator cells, or by combining these two. The efficiency of practical solar cells is determined by several loss mechanisms. An overview of efficiencies achieved through 1999 for different cells and modules is given in table 7.10.

Solar cells and their corresponding modules can be divided into two main categories: wafer-type and thin-film. Wafer-type cells are made from silicon wafers cut from a rod or ingot, or from silicon ribbons. Thin-film cells are deposited directly onto a substrate (glass, stainless steel, plastic). For flat-plate applications, the individual cells are connected in series to form a module. Solar cells for concentrator systems are mounted in a one-dimensional or two-dimensional optical concentrator.

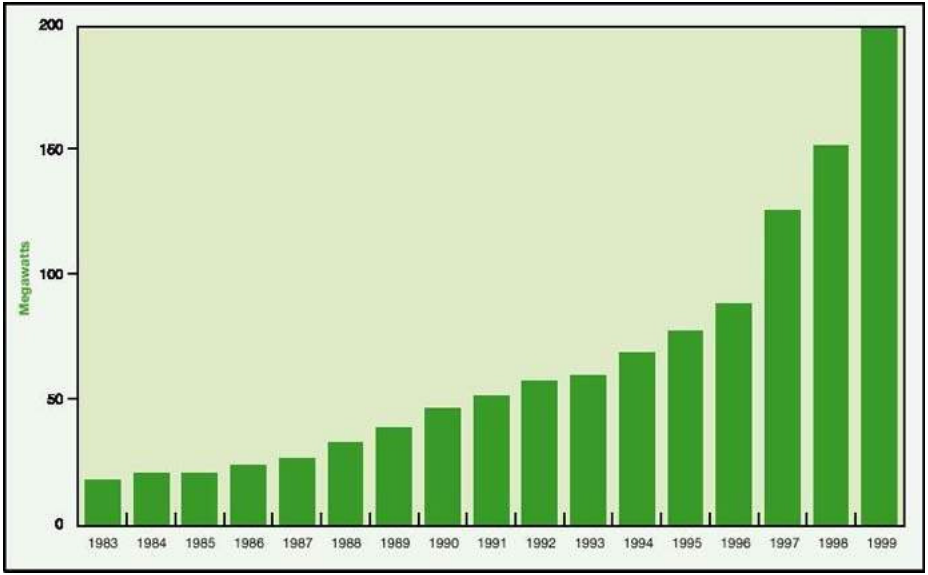

FIGURE 7.5. PHOTOVOLTAIC SHIPMENTS, 1983 - 1999

Source: Based on a Maycock, 1998; PVIR, 1999.

TABLE 7.10. IMPORTANT PHOTOVOLTAIC SOLAR CELL AND MODULE TECHNOLOGIES

Technology	Symbol	Characteristic	Record efficiency laboratory cells (percent)	Typical efficiency commercial flat-plate modules (percent)
Single crystal silicon	sc-Si	Wafer-type	24	13 - 15
Multi-crystalline silicon	mc-Si	Wafer-type	19	12 - 14
Crystalline silicon films on ceramics	f-Si	Wafer type	17	(8 - 11)
Crystalline silicon films on glass		Thin film	9	
Amorphous silicon (including silicon-germanium tandems)	a-Si	Thin film	13	6 - 9
Copper-indium/gallium-diselenide	CIGS	Thin film	18	(8 - 11)
Cadmium telluride	CdTe	Thin film	16	(7 - 10)
Organic cells (including dye-sensitised titanium dioxide cells)		Thin film	11	
High-efficiency tandem cells	III-V	Wafer-type and thin film	30	
High-efficiency concentrator cells	III-V	Wafer-type and thin-film	33 (tandem) 28 (single)	

Note: Numbers in parentheses are results from pilot production or first commercial production.

Source: Green and others, 1999.

For the technologies in table 7.10, sc-Si, mc-Si, and a-Si are fully commercial, with the first two taking 85 percent of the 1998 commercial market, and the third 13 percent. (PVIR, 1999). CIGS and CdTe are emerging commercial technologies, whereas f-Si and one form of crystalline silicon films on glass appear to be in a pilot production phase. Organic cells are still in a laboratory stage, though dye-sensitised titanium dioxide cells are considered for near-term indoor applications. High-efficiency cells are used in concentrator systems.

It is still too early to identify winners or losers among the photo-voltaic technologies under development or in production. There is reasonable consensus that thin-film technologies generally offer the best long-term perspective for very low production cost. But crystalline silicon wafer technology also still has a huge potential for cost reduction through economies of scale and technological improvements. This perspective recently triggered major investments in new production capacity. So it is not yet clear when thin films will become dominant in the photovoltaics market.

The conversion efficiency of commercial modules should increase steadily over the next decades (irrespective of the technology). For the medium term (2010) the efficiency is likely to be about 12 - 20 percent (Maycock, 1998), and for the longer term (beyond 2020) possibly 30 percent or even somewhat more (EUREC Agency, 1996). Note, however, that this is based on an evaluation of what is physically possible, not on what could be done technologically at low cost. Moreover, it is not expected that these high efficiencies can be obtained by simple extrapolation of today’s commercial technologies. It is not very likely that modules with the lowest manufacturing cost per watt have the highest efficiency.

System aspects

Photovoltaic system components. To make use of the electricity from photovoltaic cells and modules, one has to build a complete system, also comprising electronic parts, support structures, and sometimes electricity storage. It is customary to use the term balance-of-system (BOS) for the sum of system components and installation excluding modules.

Type and size of photovoltaic systems. Photovoltaics can be used in a wide variety of applications, from consumer products and small standalone units for rural use (such as solar home systems and solar lanterns) to grid-connected rooftop systems and large power stations. Typical system size varies from 50 watts to 1 kilowatt for standalone systems with battery storage, from 500 watts to 5 kilowatts for rooftop grid-connected systems, and from 10 kilowatts to many megawatts for grid-connected ground-based systems and larger building-integrated systems. Of these market segments, rural electrification for sustainable development and building-integrated systems (as forerunners of large-scale implementation) are expected to grow rapidly because of concentrated marketing efforts and financial incentives.

Need for storage. Because photovoltaic modules offer an intermittent source of energy, most standalone systems are equipped with battery storage (usually a lead-acid battery) to provide energy during the night or during days with insufficient sunshine. In some cases batteries store energy during longer periods. When using grid-connected photovoltaic systems, the grid serves as ‘virtual storage’: electricity fed into the grid by photovoltaics effectively reduces the use of fuel by power plants fired by coal, oil, or gas.

Performance ratio of photovoltaic systems. It is of great practical importance to be able to predict the actual energy that a photo-voltaic system of a certain size feeds into the grid. But that requires reliable information on the insolation in the plane of the system, on the

system power under standard test conditions, and on the system losses. For simplicity, all system losses in grid-connected photo-voltaic systems are taken together in the performance ratio, which is the ratio of the time-averaged system efficiency to the module efficiency under standard conditions. For grid-connected photo-voltaic systems the state-of-the-art performance ratio, now typically 0.75 - 0.85, could increase to 0.9 in the longer term. For state-of-the-art standalone systems the typical performance ratio is 0.6.

Environmental aspects

Environmental life-cycle analysis. Solar technologies do not cause emissions during operation, but they do cause emissions during manufacturing and possibly on decommissioning (unless produced entirely by 'solar breeders'). With the industry growing, there is now considerable interest in environmental aspects of solar technologies. Environmental life-cycle analyses of photovoltaic systems and components (Alsema and Nieuwlaar, 1998) are already leading to the development of different materials and processes in the manufacturing of photovoltaic modules (see Tsuo and others, 1998). An example is developing water-based pastes instead of pastes based on organic solvents for screen printing. In addition, several recycling processes have been developed for off-spec or rejected modules.

Energy payback time. One of the most controversial issues for photovoltaics is whether the amount of energy required to manufacture a complete system is smaller or larger than the energy produced over its lifetime. Early photovoltaic systems were net consumers of energy rather than producers. In other words, the energy payback time of these systems was longer than their lifetime. This situation has changed and modern grid-connected rooftop photovoltaic systems now have payback times much shorter than their (expected) technical lifetime of roughly 30 years (Alsema, Frankl, and Kato, 1998) (table 7.11).

For grid-connected ground-based systems the energy payback time of the balance of

system is longer than for rooftop systems, because of materials used in foundation and support. The energy payback time, now three to nine years, will decrease to one to two years.

For standalone photovoltaic systems with battery storage (such as solar home systems) the situation is less favourable than for grid-connected systems, because of the long energy payback time associated with the (lead-acid) battery. At an insolation of 2,000 kilowatt-hours per square metre a year, the energy payback time of modern solar home systems is now seven to 10 years (Alsema and Nieuwlaar, 1998). This number may come down to roughly six years, of which five are due to the battery. Since the technical lifetime of a battery in a photovoltaic system is usually five years or less, the direct effectiveness of (present generation) solar home systems for the reduction of greenhouse gas emissions is a matter of debate.

The total average power available at the Earth's surface in the form of solar radiation exceeds the total human power consumption by roughly a factor of 1,500.

Carbon dioxide mitigation potential. The carbon dioxide mitigation potential of photovoltaics can be roughly inferred from the data on energy payback time, assuming that emissions of greenhouse gases (SF_6 and CF_4) related to photovoltaic cell and module production are effectively minimised. As an example, a photovoltaic system with an energy payback time of two years at 1,500 kilowatt-hours per square metre a year and a technical lifetime of 30 years (ratio 1:15) will produce 15 kilowatt-hours of electricity without emissions for each kilowatt-hour of electricity ‘invested’ in manufacturing.

Specific carbon dioxide emissions are therefore fifteen times lower than those of the relevant fuel mix - the mix used in supplying the total photovoltaics industry chain with energy.

Materials availability. The crystalline silicon photovoltaics industry has so far used off-grade material from the semiconductor industry as its feedstock. Very fast growth of the crystalline silicon photo-voltaics industry would require dedicated production of ‘solar grade’ silicon (Bruton and others, 1997). Although several processes for solar grade silicon have been developed to a laboratory scale, none has been taken into commercial production. It is expected, however, that new feedstock can be made available in time if necessary. The availability of some of the elements in thin-film photovoltaic modules (like indium and tellurium) is a subject of concern. There apparently are no short-term supply limitations, but the match between demand from the photovoltaics industry and world market supply may become an issue at very large (multiple gigawatts a year) production levels (Johansson and others, 1993b). CdTe and CIGS may therefore be valuable bridging technologies (Andersson, 1998).

TABLE 7.11. ESTIMATED ENERGY PAYBACK TIME OF GRID-CONNECTED ROOFTOP PHOTOVOLTAIC SYSTEMS (YEARS)

	State of the art	Near to medium term (<10 years)	Long term
Modules			
Crystalline silicon	3 - 8	1.5 - 2.5	<1.5
Thin film	2 - 3	0.5 - 1.5	<0.5
Balance of system	<1	0.5	<0.5
Total system			
Crystalline silicon	4 - 9	2 - 3	<2

Thin film	3 - 4	1 - 2	<1

Note: Based on an insolation of 1,500 kilowatt-hours per square metre a year.

Source: Alsema, Frankl and Kato, 1998.

Health. Of special concern is the acceptance of cadmium-containing photovoltaic modules. The cadmium content of CdTe (and CIGS) modules appears to be well within limits for safe use (Alsema and Nieuwlaar, 1998). And production processes can fulfil all applicable requirements. But political and public acceptance is not automatic. Therefore, there are efforts to eliminate cadmium from CIGS modules even at the cost of a reduced efficiency. Also a closed cycle for reclaiming and recycling of disposed CdTe modules has been developed (Bohland and others, 1998).

Economic aspects

Photovoltaic system cost. The turnkey cost of a photovoltaic system is determined by the module cost and by the balance-of-system (BOS) costs, which contains the cost of all other system components, electrical installation costs, and costs associated with building integration, site preparation, erection of support structures, and so on. The turnkey price is generally 20 - 40 percent higher than the *cost.*

In 1998 photovoltaic module prices were $3 - 6 a watt, depending on supplier, type, and size of order (Maycock, 1998; IEA PVPS, 1998). The prices of complete photovoltaic systems vary widely with system type and size, and from country to country (Thomas and others, 1999; IEA PVPS, 1998). But $5 - 10 a watt for grid-connected systems and $8 - 40 a watt for standalone systems are considered representative today.

The future cost and price reduction of photovoltaic modules and systems can be evaluated in two ways. The first is by detailed analysis of manufacturing costs for a specific

technology as function of technology improvements and innovations - and of production volumes. The second is by general analysis of photovoltaic markets and industries, using a learning curve approach. (Note that the second approach deals with prices rather than costs.)

TABLE 7.12. POSSIBLE COSTS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS, BASED ON DIFFERENT EVALUATIONS OF PHOTOVOLTAIC PRODUCTION TECHNOLOGIES (APPROACH 1) (1998 DOLLARS PER WATT)

Element	1998	Short term (to 2005)	Medium term (2005 - 15)	Long term (after 2015)
Modules	3 - 4	1 - 2	0.5 - 1.0	£ 0.5
Balance of system	2 - 6	1 - 2	0.5 - 1.0	£ 0.5
Turnkey systems	5 - 10	2 - 4	1 - 2	£ 1.0

Note: Prices are 20 - 40 percent higher than costs.

> It is still too early to identify winners or losers among the photovoltaic technologies under development or in production.

- ***Approach 1.*** **For crystalline silicon technologies, the manufacturing cost of solar cell modules can be reduced from the present $3 - 4 a watt down to $1.5 - 2 a watt in the short term and to around $1 a watt in the longer term. For thin films (a-Si,**

CdTe, and CIGS), the module costs are expected to fall to $1 - 1.5 a watt in the short term, $0.5 - 1 a watt in the longer term (Carlson and Wagner, 1993; Bruton and others, 1997; Little and Nowlan, 1997; Maycock, 1998). EUREC Agency (1996, p.84) even mentions module costs as low as $0.30 a watt. The corresponding prices are again 20 - 40 percent higher.

The balance-of-system costs for rooftop and ground-based grid-connected systems are now typically $2 - 6 a watt. Improvements and economies of scale in power electronics, integration in the building process, and standardisation will enable reductions to $1 - 2 a watt in the short term, $0.5 a watt in the longer term. The turnkey system cost is therefore expected to decrease to $2 - 4 a watt in the short to medium term and to $1.0 - 1.5 a watt in the longer term. Ultimately (after 2015) system costs around or even below $1 a watt are foreseen (Johansson and others, 1993b; WEC, 1994b; Ber, 1998), resulting in prices of roughly $1 a watt (table 7.12). For such extremely low prices it is necessary to use very cheap modules with high efficiencies (15 - 30 percent), to reduce area-related balance of system costs.

- ***Approach 2.* An evaluation of the development of photovoltaic (mostly module) costs and prices using a learning curve can be found in IIASA and WEC (1998), Maycock (1998), ECN (1999b), and elsewhere. For 1975 - 97 the learning rate has been roughly 20 percent: prices have been reduced by 20 percent for each doubling of the cumulative sales. When the technology and market mature, as for gas turbines, the learning rate may fall to 10 percent (IIASA and WEC, 1998). It is not clear, however, whether this will apply to photovoltaics as well, since the range for all industries is 10 - 30 percent and the value for the semiconductor industry is roughly 30 percent (ECN, 1999a). Here it is assumed that the learning rate stays at 20 percent - and that this rate applies to the total system price, not just to the module price.**

In 1998 cumulative sales were roughly 800 megawatts. Production was about 150 megawatts. At growth of 15 percent a year (the average over the past 15 years; IEA PVPS, 1998), annual sales will double every five years - to about 3 gigawatts a year in 2020, when cumulative sales would be 25 gigawatts. As a result prices will have fallen in 2020 to a third of the 1998 level. With far more optimistic growth of 25 percent a year, annual sales would be 20 gigawatts a year in 2020, and cumulative sales 100 gigawatts. Prices will then have fallen to a fifth of the 1998 level.

Table 7.13 gives an overview of the cost estimates using a learning curve approach, for a learning rate of 20 percent (historic value). Results for a low learning rate of 10 percent are given for comparison. The projections using a learning curve approach show a somewhat slower decrease than those based on evaluations of photovoltaic production technologies. Note, however, that new technologies based on the use of thin-film solar cells can follow a different (lower) learning curve than the sum of all technologies.

Photovoltaic electricity costs. Electricity costs are determined by turnkey system costs, economic lifetime (depreciation period), interest rates, operation and maintenance costs (including possible replacement of components), electricity yields of the system (a function of insolation and thus of geographic location), insurance costs, and so on (table 7.14).

Implementation issues

Since the cost of photovoltaic electricity is now well above that of electricity from the grid, photovoltaics are implemented through two distinct paths. One is market development of commercial high-value applications. The second is stimulating the installation of grid-connected systems. Both paths are generally supported through government and international aid programs.

The first path deals mainly with standalone photovoltaic systems and (more recently but

to less extent) with small grid-connected systems for private use. The photovoltaics industry has survived the past decades by actively developing niche markets in telecommunication, leisure, lighting, signalling, water-pumping, and rural electrification. The rural market is now being actively pursued as potentially huge, since an estimated 2 billion people in developing countries do not have access to a grid (see chapter 10).

Photovoltaics are often a viable alternative for bringing small amounts of electricity (less than 1 kilowatt-hour a day) to end users. More than 300,000 solar home systems (typically 50 watts) have been installed over the past 10 years, only a very modest step towards true large-scale use (Ber, 1998). In addition a large number of even smaller systems has been sold. This rural market cannot be judged by the total peak power of the systems (300,000 x 50 watts = 15 megawatts). Even if all 2 billion people were to own a 100 watt photovoltaic system, this would contribute less than 1 exajoule of electricity to the world’s energy consumption. Instead, it is the large number of people involved that is significant - and even more that photovoltaics provide light, radio, television, and other important services to them.

A major barrier for rapid growth and very widespread use is the lack (in most countries) of properly developed financing schemes and the infrastructure for distribution, after-sales service, and so on. Financing is essential because few of those 2 billion people can pay cash of $400 for a system. But some can pay a smaller amount, or even a monthly rate of a few dollars up to tens of dollars. This widely acknowledged problem has two solutions. The first is the full commercial development of very small photovoltaic systems to meet basic needs and be paid for in cash (mainly photovoltaic lanterns and other lighting systems in the range of 5 - 20 watts). The second is financing schemes using a down payment and monthly fees of roughly $5 - 20 a lease, or fee-for-service (Ber, 1998).

For grid-connected systems it is important to distinguish between small and medium-sized decentralised systems (typically 500 watts to 1 megawatt) integrated in the built

environment and large ground-based, central systems (typically greater than 1 megawatt). Decentralised integrated systems have some advantages over central ground-based ones. Their balance of system costs are generally lower. And they have more technical and non-technical possibilities to increase their competitiveness.

Photovoltaic market development through government programs in industrialised countries (IEA PVPV, 1998) applies mainly to systems integrated in the built environment. The aim of these programs is to boost the development and application of photo-voltaic technology as an essential step towards future large-scale use. They provide market volume to the photovoltaics industry to achieve economies of scale and experience with a completely new way of sustainable (decentralised) electricity generation. Clearly, this policy-driven market depends on public support and high expectations for photovoltaics as a major electricity source for the future.

TABLE 7.13. POSSIBLE EVOLUTION OF TYPICAL COSTS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS USING A LEARNING CURVE (APPROACH 2)

	1998	**Medium term (2010)**		**Long term (2020)**	
Average annual market growth rate (percent)	**15 (1983 - 98)**	**15**	**25**	**15**	**25**
Annual sales (gigawatts)	0.15	0.8	2	3	20
Cumulative sales (gigawatts)	0.8	6	11	25	100
Turnkey system price (1998 dollars per watt) at a learning rate of 20 percent	5 - 10	2.7 - 5.3	2.2 - 4.3	1.7 - 3.3	1 - 2
Turnkey system price (1998 dollars per watt) at a learning rate of 10 percent	5 - 10	3.7 - 7.4	3.4 - 6.8	3.0 - 5.9	2.4 - 4.8

TABLE 7.14 ELECTRICITY COST AS A FUNCTION OF COST, ECONOMIC LIFETIME, AND ELECTRICITY YIELD OF PHOTOVOLTAIC SYSTEMS (DOLLARS A KILOWATT-HOUR)

Turnkey system cost (dollars a watt)	**Economic lifetime (years)**	**Electricity yield (kilowatt-hours a year per kilowatt of installed capacity)**	
		750	**1,500**
5	10	1.00 - 1.22	0.51 - 0.61
(lower limit 1998)	25	0.61 - 0.87	0.31 - 0.44
1	10	0.12 - 0.24	0.10 - 0.12
(long term)	25	0.12 - 0.17	0.06 - 0.09

Note: Operation and maintenance and insurance costs are 2 percent of the annual system cost. The interest rate is 5 - 10 percent.

BOX 7.6 SELECTED NATIONAL AND INTERNATIONAL PHOTOVOLTAIC PROGRAMMES

Japan. In 1994 the Japanese government adopted the New Energy Introduction Outline, with targets for renewable energy technologies, including photovoltaics. The aim is to install 400 megawatts of (mainly residential grid-connected) photovoltaic systems by 2000 and 4,600 megawatts by 2010 (Luchi, 1998). The program is based on gradually decreasing subsidies (starting at 50 percent) and net metering.

United States. The Million Solar Roofs program aims to install 1,000,000 solar hot water systems and photovoltaic systems by 2010 (IEA PVPS, 1998; Ber, 1998). The trend is from demonstrations and tests towards market-centred projects with funding primarily from the private sector. The program works by creating partnerships between communities, federal agencies, and the Department of Energy (Rannels, 1998).

Germany. The 100,000 Roofs program (300 - 350 megawatts in 2005) is dedicated to grid-connected photovoltaic systems. Private investments in photovoltaics are stimulated by interest-free loans and a subsidy of 12.5 percent (Photon, 1999b). In addition, the government decided recently to pay nearly 1 deutsche mark a kilowatt-hour to owners of photovoltaic systems, financed by a small increase of electricity rates.

Italy. The 10,000 Rooftops program aims to install 50 megawatts by around 2005 (Garrozzo and Causi, 1998). With a focus on building small- and medium-sized integrated, grid-connected photovoltaic systems, funding may be mixed public (75 percent) and private (25 percent).

European Union. The target for photovoltaics is an installed capacity of 3 gigawatts by 2010. This has been translated into a Million Roofs program to install 500,000 grid-connected photovoltaic systems on roofs and facades in the Union and to export another 500,000 village systems for decentralised electrification in developing countries (EC, 1997; EC, 1999; IEA PVPS, 1998).

Indonesia. In 1998 the installed capacity of photovoltaic systems in Indonesia was 5 megawatts. A new strategy has been developed to enhance the use of renewable energy technologies, especially photovoltaics. Some characteristics of this strategy are: establish renewable energy non-governmental organisations, prepare renewable energy product standards, run demonstration projects in partnership with the private sector, provide training, disseminate information, strengthen international cooperation, and institute policy development and regulation.

India. With a total installed capacity of about 40 megawatts of photovoltaic systems, India has among the world’s largest national programs in photovoltaics. The five-year national plan 1997 - 2002 envisages a deployment of 58 megawatts in addition to the 28 megawatts installed as of 1997. Exports of 12 megawatts are also foreseen. Government-sponsored programs include installing solar lanterns and other lighting systems - and electrifying villages and grid-connected power plants. Subsidies are available to rural users (Sastry, 1999).

South Africa. Shell Renewables Ltd. and Eskom are investing $30 million in rural solar power development in South Africa from 1999 until 2001. This venture should provide standalone photovoltaic units to about 50,000 homes presently without electricity at a cost of about $8 a month (see chapter 10).

Kenya. Kenya has a high penetration rate of household photo-voltaic systems. In 1999 more than 80,000 systems were in place and annual sales are about 20,000 systems. The market operates without significant external aid or support (see chapter 10).

World Bank. The World Bank has become very active in developing financial schemes and programs for rural electrification in developing countries (Photon, 1999a). An example is the photo-voltaic Market Transformation Initiative. The Bank's activities, fully integrated on a national level, mainly aim at removing barriers and building capacity. Generally, the approach is not to stimulate photovoltaics through subsidies for system hardware, but to facilitate commercial operations fitted to the local circumstances.

A variety of instruments can achieve a self-sustained market: rate-based measures (favourable feed-in tariffs), fiscal measures, investment subsidies, soft loans, building codes. Another instrument is the removal of barriers related, say, to building design and material use. In addition to these incentives, the added value of photovoltaics - like aesthetics in building integration, combining electricity generation and light transmission, and generating part or all of one's own electricity consumption - are used in marketing photovoltaics. Green electricity and green certificates for the use of renewables are also expected to be important in the further development of a self-sustained market for grid-connected systems. They enable selling electricity from photovoltaics (or other renewables) to environmentally conscious electricity consumers.

Several countries have set targets or formulated programs for renewable energy technologies, specifically solar (box 7.6). In countries with a well-developed electricity infrastructure, the long-term aim is to achieve a substantial contribution to the electricity

generation from solar energy. In developing countries and countries with a less-developed electricity infrastructure, efforts are focused on the large-scale implementation of smaller standalone solar photovoltaic systems. In these cases the dissemination of solar energy is a tool for social and economic development.

Space-based solar energy

A very different approach to exploiting solar energy is to capture it in space and convey it to the Earth by wireless transmission. Unlike terrestrial capture of solar energy, a space-based system would not be limited by the vagaries of the day-night cycle and adverse weather - and so could provide baseload electricity (Glaser and others, 1997).

In space the maximum irradiance (power density) is much higher than on Earth - around 1,360 watts per square metre - and is nearly constant. This energy can be captured and converted to electricity just as it can on Earth, as is done routinely to power spacecraft. The elements of such a space-based solar energy system would include:

- **Satellites in geosynchronous or other orbits designed as large solar collectors.**
- **Power conditioning and conversion components to turn the electricity generated by the photovoltaic arrays into radio frequency form.**
- **Transmitting antennas that form one or more beams directed from the satellites to the Earth.**
- **Receiving antennas on Earth that collect the incoming radio frequency energy and convert it into useful electricity. Such a device is called a rectenna (for rectifying receiving antenna). The power yield from typical rectennas at low to middle latitudes would be on the order of 30 megawatts per square kilometre.**

- **Power conditioning components to convert the direct current output from the rectenna to alternating current for local use.**

As with any solar source, space-based energy would not contribute to greenhouse gas emissions during operation. The high launch rate required to place a space-based energy system could affect the Earth's atmosphere, however. The effects of power transmission to the ground need to be assessed for at least three factors: influences on the atmosphere (particularly the ionosphere on the way down), inference between the wireless power transmission and communications or electronic equipment, and the effects of the transmitted beam on life forms. Estimates and some experiments indicate that these effects might be small.

Very preliminary estimates suggest that a cost target of $0.05 per kilowatt-hour may ultimately be achievable for a mature space-based solar energy system (Mankins, 1998). But several important issues must be addressed:

- **A number of key technologies require maturation.**
- **The cost of access to space must be substantially lowered.**
- **Safety and environmental concerns must be resolved.**
- **Optimal designs for space-based solar systems need to be established.**
- **Orbital slots for collecting platforms and frequencies for power transmission need to be obtained.**

Conclusion

- **Since 1983 the average growth rate of photovoltaic module shipments has been 15 percent a year. In 1998 the production was 150 megawatts, and in 1999, about 200 megawatts. In 1998 the cumulative production was around 800 megawatts, with the operating capacity probably about 500 megawatts, perhaps 600 megawatts. The growth of operating photovoltaic capacity in the last five years can**

be estimated at roughly 30 percent a year.

- **Since 1975 the learning rate (cost reduction as function of cumulative production) has been roughly 20 percent. In 1998 turnkey costs of grid-connected photovoltaic systems were $5 - 10 a watt. In the future these costs may come down to about $1 a watt.**

- **Today photovoltaics generally cannot compete with conventional power plants in grid-connected applications. Photovoltaic electricity production costs are about $0.3 - 1.5 a kilowatt-hour, depending on solar insolation, turnkey costs, depreciation periods, and interest rates. Under favourable conditions and at favourable sites, the lowest cost figure may come down to $0.05-0.06 a kilowatt-hour.**

- **It remains uncertain whether and when photovoltaics will compete with fossil fuels on a large scale. This mainly depends on the development of photovoltaics, on the price development of coal and natural gas, and on possibilities for (or policies on) carbon dioxide removal at low cost.**

- **Supplying less than 1 percent of the world's energy consumption, photovoltaic systems can play a major role in rural electrification by reaching many of the 2 billion people in developing countries who do not have access to electricity.**

- **There appear to be no invincible technical problems for solar energy to contribute much to the world's energy supply. What matters are policy developments and the market position of fossil fuels and other energy sources.**

Photovoltaics are often
a viable alternative for bringing
small amounts of electricity (less

than 1 kilowatt-hour a day) to end users.

Solar thermal electricity

Solar radiation can produce high-temperature heat, which can generate electricity. The most important solar thermal technologies to produce electricity - concentrating - use direct irradiation. Low cloud areas with little scattered radiation, such as deserts, are considered most suitable for direct-beam-only collectors. Thus the primary market for concentrating solar thermal electric technologies is in sunnier regions, particularly in warm temperate, sub-tropical, or desert areas. About 1 percent of the world’s desert area used by solar thermal power plants would be sufficient to generate today’s world electricity demand. Here we will assess the current status and future development of solar thermal electricity (STE) technologies.

The potential of solar thermal electricity

STE is probably 20 years behind wind power in market exploitation. In 1998 operating STE capacity was about 400 megawatts of electricity, with annual electricity output of nearly 1 terawatt-hour. New projects in mind mount to a maximum of 500 megawatts of electricity, and it is probable that 2,000 megawatts of installed capacity will not be reached until 2010 (the capacity wind reached in 1990). Because STE costs are dropping rapidly towards levels similar to those obtained by wind, STE may grow in a manner somewhat similar to wind. If the growth rate is 20 - 25 percent after 2010, this installed STE capacity would be 12,000 - 18,000 megawatts of electricity by 2020. If annual growth rate then averages 15 percent a year, the result would be 800 - 1,200 gigawatts of electricity by 2050. The Cost Reduction Study for Solar Thermal Power Plants, prepared for the World Bank in early 1999 (Enermodal, 1999), concludes that the large potential market of STE could reach an annual installation rate of 2,000 megawatts of electricity. In the foregoing

scenario this rate is reached between 2015 and 2020. Advanced low-cost STE systems are likely to offer energy output at an annual capacity factor of 0.22 or more. So, the contribution of STE would be about 24 - 36 terawatt-hours of electricity by 2020 and 1,600 - 2,400 terawatt-hours by 2050.

Solar thermal electricity market developments

STE technologies can meet the requirements of two major electric power markets: large-scale dispatchable markets comprising grid-connected peaking and baseload power, and rapidly expanding distributed markets including both on-grid and remote applications.

Dispatchable power markets. Using storage and hybridisation capabilities (integration of STE with fossil fuel power plants), dispatchable solar thermal electric technologies can address this market. Currently offering the lowest-cost, highest-value solar electricity available, they have the potential to be economically competitive with fossil energy in the longer term. With continuing development success and early implementation opportunities, the electricity production cost of dispatchable STE systems is expected to drop from $0.12 - 0.18 a kilowatt-hour today to about $0.08 - 0.14 a kilowatt-hour in 2005 and to $0.04 - 0.10 a kilowatt-hour thereafter.

In this market there is a huge existing global capacity of fossil fuel plant, much of it coal, available for low solar-fraction retrofit as a transition strategy. Coal-fired plants tend to be much larger individually than solar thermal standalone plants (600 - 1,200 megawatts of electricity compared with 5 - 80 megawatts), and usable land around coal-fired plants is restricted. Any solar retrofit to a typical coal-fired plant will supply only a small percentage of its total electricity output. But around the world, there are hundreds of such fossil fuel plants in good insolation areas, many with sufficient adjacent land area to accommodate a solar field of the size of the current largest STE units of about 80 megawatts. This market could account for a large fraction of the 12,000 - 18,000

megawatts by 2020 in the scenario above.

Distributed power markets. The majority of these applications are for remote power, such as water pumping and village electrification, with no utility grid. In these applications, diesel engine generators are the primary current competition. The STE technology appropriate for smaller distributed applications is the dish/engine system. Each dish/engine module (10 - 50 kilowatts of electricity) is an independent power system designed for automatic start-up and unattended operation. Multiple dish/engine systems can be installed at a single site to provide as much power as required, and the system can readily be expanded with additional modules to accommodate future load growth. The systems can be designed for solar-only applications, easily hybridised with fossil fuels to allow power production without sunlight, or deployed with battery systems to store energy for later use.

BOX 7.7. COMMERCIAL SOLAR THERMAL ELECTRICITY DEVELOPMENTS NOW UNDER WAY

Australia. Under the Australian Greenhouse Office (AGO) Renewable Energy Showcase Programme, a 13 megawatt-thermal compact linear fresnel reflector (CLFR) demonstration unit will be installed in 2001, retrofitted to an existing 1,400 megawatts-electric coal-fired plant in Queensland (Burbridge and others, 2000). It is expected to offer the solar electricity from this first commercial project as green power at a price below $0.09 a kilowatt-hour. A 2 megawatts-electric demonstration unit, using paraboloidal dish technology, has also been announced for installation in 2001, retrofitted to a gas-fired steam generating plant (Luzzi, 2000).

Greece. On the island of Crete, the private venture capital fund Solar Millennium - together with Greek and European industrial partners - has established the first solar thermal project company (THESEUS S.A.) and submitted an application for licensing a 52 megawatt-thermal solar thermal power plant with 300,000 square metres of parabolic trough solar field.

Spain. New incentive premiums for the generation of renewable electricity in 1999 caused Spanish companies such as Abengoa, Gamesa, and Ghersa to engage in solar thermal technologies and to establish various project companies (Osuna and others, 2000).

United States. Green electricity and renewable portfolio policies of various states have revived the interest of such industrial firms as Bechtel, Boeing, and Dukesolar in the further development of STE technologies.

Global Environment Facility. In 1999 the Global Environmental Facility approved grants for the first solar thermal projects in Egypt, India, Mexico, and Morocco - about $200 million in total. The proposed Indian plant uses integrated gas combined cycle and solar thermal (Garg, 2000).

The high value of distributed power (more than $0.50 a kilowatt-hour for some remote applications) provides opportunities for commercial deployment early in the technology development. The technology enhancements needed to achieve high reliability and reduce operation and maintenance costs are understood. With continuing development, the electricity production costs of distributed STE system are expected to drop from $0.20 - 0.40 a kilowatt-hour today to about $0.12 - 0.20 a kilowatt-hour in 2005 and to $0.05 - 0.10 a kilowatt-hour in the long run.

STE projects, ranging from about 10 kilowatts to 80 megawatts of electricity, have been realised or are being developed in Australia, Egypt, Greece, India, Iran, Jordan, Mexico, Morocco, Spain, and the United States (box 7.7).

Market entry strategy. Three phases can be distinguished in an STE market entry strategy:

- ***Solar field additions.* Small solar fields can be integrated into combined cycle and coal or fuel oil-fired power plants for $700 - 1,500 per kilowatt installed.**
- ***Increased solar share.* With increasing fossil fuel prices or compensation**

premiums for carbon dioxide avoidance as well as solar field cost reductions, the share of solar can be increased to about 50 percent in solar-fossil hybrid power stations.

- *Thermal energy storage.* With further improvement in the cost-benefit ratio of STE, thermal energy storage will further substitute for the need of a fossil back-up fuel source. In the long run, baseload operated solar thermal power plants without any fossil fuel addition are in principle possible, and clean bio-energy back-up is also feasible.

Figure 7.6 presents an outlook on the market introduction of STE technologies and the associated reduction in electricity generation costs as presented by SunLab (1999).

Solar thermal electricity technologies

Five distinct solar thermal electric conversion concepts are available, each with different operating and commercial features. Two non-concentrating technologies - solar chimney and solar pond - are not included in this brief description of emerging solar thermal power concepts, because they lack significantly sized pilot and demonstration test facilities.

All concentrating solar power technologies rely on four basic key elements: collector/concentrator, receiver, transport/storage, and power conversion. The collector/concentrator captures and concentrates solar radiation, which is then delivered to the receiver. The receiver absorbs the concentrated sunlight, transferring its heat energy to a working fluid. The transport/storage system passes the fluid from the receiver to the power conversion system. In some solar thermal plants a portion of the thermal energy is stored for later use. As solar thermal power conversion systems, Rankine, Brayton, Combined, and Stirling cycles have been successfully demonstrated.

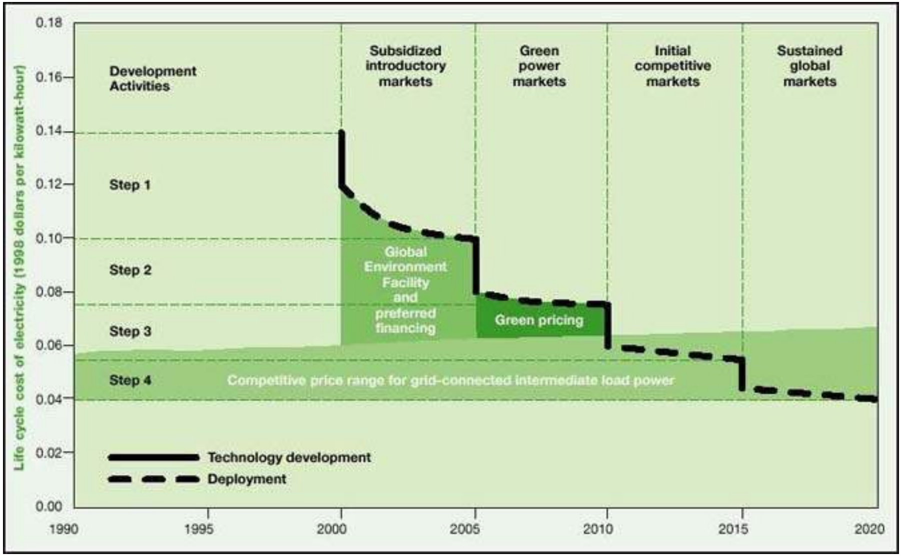

FIGURE 7.6 MARKET INTRODUCTION OF SOLAR THERMAL ELECTRICITY TECHNOLOGIES WITH INITIAL SUBSIDIES AND GREEN POWER TARIFFS, 1990 - 2020

Source: SunLab, 1999.

An inherent advantage of STE technologies is their unique ability to be integrated with conventional thermal plants. All of them can be integrated as a solar boiler into conventional thermal cycles, in parallel with a fossil-fuelled boiler. They can thus be provided with thermal storage or fossil fuel back-up firm capacity without the need for separate back-up power plants and without stochastic perturbations of the grid (figure 7.7). The potential availability of storage and ability to share generation facilities with clean biomass suggest a future ability to provide a 100 percent replacement for high

capacity factor fossil fuel plant when needed.

Parabolic trough systems. The parabolic trough (solar farm) consists of long parallel rows of identical concentrator modules, typically using trough-shaped glass mirrors. Tracking the sun from east to west by rotation on one axis, the trough collector concentrates the direct solar radiation onto an absorber pipe located along its focal line. A heat transfer medium, typically oil at temperatures up to 400 degrees Celsius, is circulated through the pipes. The hot oil converts water to steam, driving the steam turbine generator of a conventional power block.

With 354 megawatts-electric of parabolic trough solar electric generating systems connected to the grid in southern California since the mid-1980s, parabolic troughs are the most mature STE technology (Pilkington, 1996). There are more than 100 plant-years of experience from the nine operating plants. The plants range in size from 14 - 80 megawatts of electricity. Until the end of 1998, 8 terawatt-hours of solar electrical energy had been fed into the Californian grid, resulting in sales revenues of more than $1,000 million. The technology is under active development and refinement to improve its performance and reduce production costs.

Central receiver/power tower. The solar central receiver or power tower is surrounded by a large array of two-axis tracking mirrors - termed heliostats - reflecting direct solar radiation onto a fixed receiver located on the top of the tower. Within the receiver, a fluid transfers the absorbed solar heat to the power block where it is used to heat a steam generator. Water, air, liquid metal, and molten salt have been tested as fluids.

Advanced high-temperature power tower concepts are now under investigation, heating pressurised air to more than 1,000 degrees Celsius to feed it into the gas turbines of modern combined cycles. In Barstow, California, a 10 megawatts-electric pilot plant (Solar One) operated with steam from 1982 - 88. After modification of the complete plant in

1996, it operated as Solar Two for a few thousand hours, with molten salt as the heat-transfer and energy-storage medium, delivering power to the electricity grid on a regular basis (Pacheco and others, 2000). The net solar-electric conversion efficiency was 8 percent. Solar Two has demonstrated, through storage, the feasibility of delivering utility-scale solar power to the grid 24 hours a day, if necessary (Kolb, 1998). In parallel, European activities have demonstrated the volumetric air receiver concept, where the solar energy is absorbed on fine-mesh screens and immediately transferred to air as the working fluid (Buck and others, 2000).

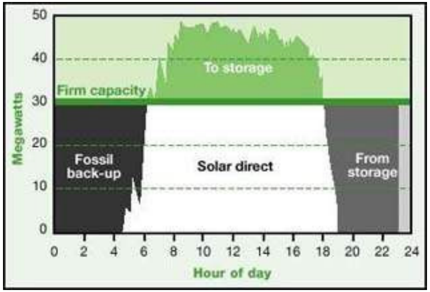

FIGURE 7.7. WITH MINIMAL FOSSIL BACK-UP AND THERMAL ENERGY STORAGE, SOLAR CAPACITY IS TRANSFORMED INTO FIRM CAPACITY

Source: Geyer, 1999.

Dish/engine power plants. Parabolic dish systems consist of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is often used directly by a heat engine, mounted on the receiver. Stirling and Brayton cycle engines are currently favoured for decentralised power conversion. Central Rankine cycles are being studied for large fields of such dishes where the receiver does not contain a heat engine.

Several dish/engine prototypes have operated successfully in the last 10 years, including 7 - 25 kilowatts-electric units developed in the United States. But there has not yet been a large-scale deployment. In Spain six units with a 9 - 10 kilowatts-electric rating are operating successfully. Australia has demonstrated a 400 square metre, 10 kilowatts-electric ‘big dish’ at the Australian National University in Canberra (Luzzi, 2000). Work is proceeding to develop a dish plant of 2 - 3 megawatts- electric attached to an existing fossil fuel power plant.

Advanced systems under development. Compact linear fresnel reflector (CLFR) technology has recently been developed at the University of Sydney in Australia. Individual reflectors have the option of directing reflected solar radiation to at least two towers. This additional variable in reflector orientation provides the means for much more densely packed arrays. The CLFR concept, intended to reduce costs in all elements of the solar thermal array, includes many additional features that enhance system cost and performance. The technology aims only at temperatures suitable for steam boilers and pre-heaters, with the view that superheating is a minor input and can be done by other fuels.

Fuels. Long-term research is under way in Australia, Germany, Israel, Switzerland, and elsewhere to produce solar fuels for a range of uses, including fuel cells for electricity production. This work is targeted towards the thermochemical conversion of solar energy into chemical energy carriers (hydrogen, synthesis gas, metals).

Economic aspects

The Cost Reduction Study for Solar Thermal Power Plants (Enermodal, 1999) has assessed the current and future cost competitiveness of STE with conventional power systems for two STE technologies: the parabolic trough and the molten salt central receiver system. Two approaches were used to assess the future cost performance of these technologies: an engineering approach based on known technical improvements and cost reductions

from commercialisation, and a learning (experience) curve approach. The two approaches yielded similar results.

Costs per kilowatt of trough plants are expected to fall from $3,000 - 3,500 a kilowatt in the near term (for a 30 megawatts-electric plant) to $2,000 - 2,500 a kilowatt in the long term (for a 200 megawatts-electric plant). For central receiver systems these figures are $4,200 - 5,000 a kilowatt in the near term and $1,600 - 1,900 a kilowatt in the long term. The attainable net solar-to-electric conversion efficiencies of these systems are expected to be 13 - 16 percent in the near term and 18 - 20 percent in the long term. Operation and maintenance costs can decrease from about $0.025 a kilowatt-hour in the near term to about $0.005 a kilowatt-hour in the long term.

If the cost of electricity from conventional power plants stays constant over the next 20 years, the solar levelised energy cost (LEC) can be calculated to fall to less than half of current values - from $0.14 - 0.18 a kilowatt-hour to $0.04 - 0.06 a kilowatt-hour. At this cost, the potential for STE power plants to compete with Rankine cycle plants (coal, gas, or oil fired) can be promising. The solar LEC for the tower is calculated to be less than for the trough because of the use of thermal storage. If troughs were equipped with storage as well, the same advantage would probably be found. It can thus be concluded that 24-hour power does not increase the total generating costs. If a credit of $25 - 40 a tonne were included for reduced carbon dioxide emissions, STE power may have an even lower LEC than coal-fired Rankine plants.

Environmental and social aspects

Carbon dioxide emission savings. A solar boiler can supply 2,000 to 2,500 full load hours per year to a steam cycle. With STE technologies, each square meter of solar field can produce up to 1,200 kilowatt- hours of thermal energy a year - or up to 500 kilowatt-hours of electricity a year. Taking into account a thermal plant carbon dioxide emissions of

0.4 - 0.8 kilograms a kilowatt-hour electric, there results a cumulative saving of up to 5 - 10 tonnes of carbon dioxide per square metre of STE system over its 25-year lifetime (Pilkington, 1996).

Impact on fossil fuels consumption. The embodied energy of a STE plant is recovered after less than 1.5 years of plant operation (Lenzen, 1999). STE systems can preserve fossil energy or biomass resources. Taking into account an average conventional thermal power plant efficiency of 40 percent, there results a cumulative saving of about 2.5 tonnes of coal per square metre of solar field over its 25-year lifetime.

Land use. Land use is sometimes cited as a concern with renewables. If renewables are to contribute to energy production on a global scale, sufficient areas have to be available in suitable locations. Most solar thermal power plants need about 1 square kilometre of area for 60 megawatts of electricity capacity, although STE technologies like CLFR (see above) might reduce this by a factor or 3 or so (Mills and Morrison, 2000a, b).

Domestic supply of equipment and materials. The higher up-front cost of solar thermal power stations results from the additional investment into the STE equipment and erection. Most of this equipment and most of the construction materials required can be produced domestically. The evaluation of the domestic supply capability of selected countries indicates national supply shares ranging from 40 percent to more than 50 percent of the total project value. This supply share can be increased for subsequent projects (Pilkington, 1996).

Labour requirements. The erection and operation of the nine STE power plants in California indicate current labour requirements. The last 80 megawatts-electric plants showed that during the two-year construction period, there is a peak of about 1,000 jobs. Operation of the plant requires about 50 permanent qualified jobs (Pilkington, 1996).

Conclusion

- **In the sunbelt of the world, solar thermal power is one of the candidates to provide a significant share of renewable clean energy needed in the future.**

- **STE is now ready for more widespread application if we start more intensified market penetration immediately; its application is not strongly restricted by land area or resource limitations.**

- **The STE technology appropriate for smaller remote power production is the dish/engine power plant. For grid-connected applications, technologies such as the parabolic trough system and the central receiver/power tower are applied.**

- **The installed STE capacity, now about 400 megawatts of electricity, may grow to 2,000 megawatts of electricity in 2010 - and to 12,000 - 18,000 megawatts of electricity in 2020. An annual growth rate of 15 percent after 2020 would yield 1,600 - 2,400 terawatt-hours a year by 2050.**

- **Small solar fields can be integrated into fossil fuel power plants at relatively low costs. With improvement of the cost-benefit ratio of STE, the solar share in hybrid solar/fossil power plants may increase to about 50 percent. Thermal energy storage will be able to further substitute for the need for a fossil back-up fuel. In the long run, baseload-operated solar thermal power plants without any fossil fuel addition are now technically proven.**

- **STE is the lowest-cost solar electricity in the world, promising cost competitiveness with fossil fuel plants in the future - especially if assisted by environmental credits. Electricity production costs of grid-connected STE systems may come down from $0.12 - 0.18 a kilowatt-hour today to $0.04 - 0.10 a kilowatt-hour in the long term. In remote areas, the production costs of distributed systems may come down from $0.20 - 0.40 a kilowatt-hour today to $0.05 - 0.10 a kilowatt-hour in the long term.**

The easiest and most direct application of solar energy is the direct conversion of sunlight into low-temperature heat.

Low-temperature solar energy

The easiest and most direct application of solar energy is the direct conversion of sunlight into low-temperature heat - up to a temperature of 100 degrees Celsius. In general, two classes of technologies can be distinguished: passive and active solar energy conversion. With active conversion there is always a solar collector, and the heat is transported to the process by a medium. With passive conversion the conversion takes place in the process, so no active components are used.

In this section the main focus is on active conversion, for which a broad range of technologies is available. The best known is the solar domestic hot water system. Another technology in the building sector is the solar space heating system. Such a system can be sized for single houses or for collective buildings and district heating. Similar technologies can be applied in the industrial and agricultural sector for low-temperature heating and drying applications. Heating using solar energy can also be achieved by heat pumps. Finally, there are technologies to use solar energy for cooling and cooking purposes.

Low-temperature solar energy potential and market developments

The world’s commercial low-temperature heat consumption can be estimated at about 50 exajoules a year for space heating and at about 10 exajoules a year for hot water production. Low- and medium-temperature heat (up to 200 degrees Celsius) is also used as process heat, in total about 40 exajoules a year. Almost any low-and medium-temperature heat demand can be met at least partially with solar energy. One of the

drawbacks for this application is the mismatch between availability of sunlight and demand for heating. Therefore nearly any solar heating system contains a storage unit.

The solar domestic hot water system (SDHW) is the most important application for low-temperature solar heat at this moment. In 1994 some 7 million SDHWs had been installed world-wide. In 1994 the total installed collector area of SDHWs and other solar energy systems was about 22 million square metres (Morrison, 1999) and in 1998 about 30 million square metres. This can be expressed as an installed capacity of around 18,000 megawatts. The total amount of heat generated by these solar energy systems can be estimated roughly at 50 petajoules a year. This is only 0.5 percent of the potential of around 10 exajoules a year. Table 7.15 provides an overview of the annually produced and total installed glazed collector area.

In Europe the market rapidly expanded after 1994. In 1996 about 700,000 square metres were produced, mainly in Germany (330,000 square metres) and Austria (230,000 square metres). The European Solar Industry Federation expects annual growth of around 20 percent (ESIF, 1996). In 1998 sales in Europe were probably on the order of 1 million square metres. In the United States the market has declined - the amount of collector area sold in SDHW systems decreased from 1.1 million square metres in 1984 to around 80,000 square metres in 1998 (Morrison, 1999). The market collapsed in 1986 because the federal R&D funding and tax credits ended abruptly. In China production is increasing rapidly. In Japan the market is increasing after a collapse in 1987 (ESIF, 1996). For different regions, growth of 10 - 25 percent a year is foreseen. In 2010 the installed collector area could be 150 million square metres.

TABLE 7.15. MAJOR SOLAR COLLECTOR MARKETS, 1994 (THOUSANDS OF SQUARE METRES)

Economy	Total glazed collector area installed	Glazed collector area produced

Australia	**1,400**	**140**
China	**1,500**	**500**
India	**500**	**50**
Israel	**2,800**	**300**
Japan	**7,000**	**500**
Taiwan, China	**200**	**90**
United States	**4,000**	**70**
Europe	**4,700**	**500**
Austria	400	125
Cyprus	600	30
France	260	18
Germany	690	140
Greece	2,000	120
Portugal	200	13
World	**~ 22,000**	**~ 2,200**

Source: Based on Morrison, 1999.

TABLE 7.16. CHARACTERISTICS OF SOLAR DOMESTIC HOT WATER SYSTEMS IN EUROPE

Feature	Northern Europe	Central Europe	Mediterranean
Collector area (square metres)	**3 - 6**	**3 - 5**	**2 - 4**
Storage capacity (litres)	**100 - 300**	**200 - 300**	**100 - 200**
Annual system performance(kilowatt-hours per	**300 - 450**	**400 - 550**	**500 - 650**

Annual system performance(kilowatt-hours per square metre)	[illegible]	[illegible]	[illegible]
Installed system costs(dollars per square metre)	**400 - 1,000**	**400 - 1,000**	**300 - 600**[a]
Common system type	**Pump/ circulation**	**Pump/ circulation**	**Thermosyphon**

a. In countries like Israel and Turkey this figure can be even lower.

Another important technology is the electric heat pump. Driven by electricity, this pump can withdraw heat from a heat source and raise the temperature to deliver the heat to a process (such as space heating). Tens of millions of appliances have been installed that can be operated as heat pumps, while most of them can also be operated as cooling devices (air conditioners). Whether the application of these machines results in net fuel savings depends on the local situation, taking into account aspects such as the performance of the heat pump, the reference situation, and characteristics of the electricity source. A lack of data makes it impossible to determine the net contribution of heat pumps to the energy supply.

Low-temperature solar energy technologies and systems

Solar domestic hot water systems. The solar domestic hot water system (SDHW) consists of three components: a solar collector panel, a storage tank, and a circulation system to transfer the heat from the panel to the store. SDHW systems for household range in size, because of differences in hot water demands and climate conditions. In general price/performance analysis will be made to size the solar hot water system and to investigate the optimum solar fraction (contribution of solar energy in energy demand). The results show a general dependence on the climate. The SDHW systems in Northern and Central Europe are designed to operate on a solar fraction of 50 - 65 percent. Subtropical climates generally achieve solar fractions of 80 - 100 percent. Table 7.16

indicates typical characteristics of applied systems in various climate zones in Europe.

Pump/circulation systems are generally used in climate zones with a serious frost and overheating danger. These systems either use the drain-back principle (the fluid drains from the collector if there is no solar contribution) or an antifreeze additive in the collector fluid. In countries with a warmer climate, natural circulation systems are mostly used. Almost all collectors installed are of the flat plate type. But in China in 1997 about 2 million evacuated tube collectors (about 150,000 square metres of collector area) were produced (Morrison, 1999). These are double-walled concentric glass tubes, of which the enclosed space is evacuated. In regions with high solar irradiation, the use of SDHW systems may result in solar heat production costs ranging from $0.03 - 0.12 a kilowatt-hour.

In regions with relatively low solar irradiation, the costs may range from $0.08 - 0.25 a kilowatt-hour. In many areas these costs can be competitive with electricity prices - but in most cases not with fossil fuel prices. Further cost reductions are therefore required.

- **One approach is the use of complete prefabricated systems or kits, leaving no possibility to make changes in the system design, thus simplifying the installation work and reducing both the hardware and the installation cost.**

- **Another approach, in Northern Europe, is the development of solar thermal energy markets on a large scale, to reduce production, installation, and overhead costs. As demonstrated in the Netherlands, large projects can reduce the installed system price by 30 - 40 percent relative to the price of individually marketed systems.**

- **Cost reductions can also be achieved by further development of the technology (including integration of collector and storage unit). As a result of these approaches, solar heat production costs may come down 40 - 50 percent (TNO,**

1992).

SDHW systems are commonly produced from metals (aluminium, copper, steel), glass and insulation materials. In most designs the systems can easily be separated into the constituent materials; all metals and glass can be recycled. The energy payback time of a SDHW system is now generally less than one year (van der Leun, 1994).

Large water heating systems. Solar thermal systems can provide heat and hot water for direct use or as pre-heated water to boilers that generate steam. Such large water heating systems find widespread use in swimming pools, hotels, hospitals, and homes for the elderly. Other markets are fertiliser and chemical factories, textile mills, dairies, and food processing units. Substantial quantities of fossil fuels or electricity can be saved through their use. But the installed collector area is rather low - around a tenth of the total installed area. It is especially low in the industrial sector, mainly because of low fossil fuel costs and relatively high economic payback times of solar systems. India provides tax benefits through accelerated depreciation on such commercial systems and also has a programme to provide soft loans to finance their installation. Within these systems about 400,000 square metres of collector area has been installed in India (TERI, 1996/97). The costs per kilowatt-hour of large water heating systems are now somewhat less than SDHW energy costs. And in the long term these costs can be reduced, probably about 25 percent, mainly by mass production.

Solar space heating. Total world space heating demand is estimated at 50 exajoules a year. In northern climates this demand can be more than 20 percent of total energy use. Mismatch between supply and demand limits the direct contribution of solar thermal energy to the space heating of a building to a maximum of 20 percent in these regions. If seasonal storage of heat is applied, solar fractions of up to 100 percent are achievable (Fisch, 1998). Space heating systems are available as water systems and as air heating systems, with air heating systems generally cheaper. Water-based systems are usually

solar combi-systems that supply domestic hot water and space heating.

Seasonal storage has mainly been applied in demonstration projects, showing its technological feasibility. The technologies are divided into large and small systems. For large systems (storage for more than 250 houses) the insulation is not so important, and duct storage or aquifer storage is possible. For small systems storage of heat in an insulated tank is the only solution to date. More advanced concepts - such as chemical storage of heat - have been proven on a laboratory scale. Storage of cold from the winter to be used in the summer has proven to be profitable, if aquifers are available in the underground.

Passive solar energy use has become an attractive optionfor heating and cooling buildings because of the development of new materials and powerful simulation tools

District heating. Solar energy can also be applied for district heating. Providing hot water and space heat, several of these systems, using a central collector area, have been realised in Denmark, Germany, and Sweden. They reach similar solar fractions as single house systems: 50 percent for hot water production and 15 percent for the total heat demand (hot water plus space heating). Some of these systems have been combined with a seasonal storage increasing the solar fraction to 80 percent for the total heat demand.

Heat pumps. Heat pumps can generate high-temperature heat from a low-temperature heat source. Working in the opposite direction the same appliance can also be used as a cooling device. In fact most heat pumps are air conditioners that are also suitable for heating purposes. Tens of millions of these appliances have been installed world-wide. In

colder climates there is a market for heat pumps for heating only. In Europe in 1996 around 900,000 of these pumps were installed (Laue, 1999), and the market is growing at about 10 percent a year (Bouma, 1999).

Energy (mostly electricity) is needed to operate the heat pump. Typically the heat energy output is two to four times the electrical energy input. The low-temperature heat input can come directly or indirectly from the sun. For example, with ground-coupled heat pump systems, the surface can be seen as a cheap solar collector - and the ground beneath it as a storage system from which the low-temperature heat can be extracted. Today, however, most systems extract heat from the open air. Different systems have been tested using solar collectors as a heat source. Because heat pumps can work with low temperatures, the collectors can be cheap.

No general statement can be made about the contribution of heat pumps to savings in fossil fuel consumption and environmental emissions. But by further improving the performance of the heat pump and by using electricity from renewable sources (hydro, wind, photovoltaics), this contribution will be definitely positive.

Solar cooling. About 30 million air conditioners are sold each year (Nishimura, 1999). Cooling with solar heat seems an obvious application, because demand for cooling and supply of solar heat are in phase. The technologies available are absorption cooling, adsorption cooling, and desiccant cooling. A standard, single-effect absorption chiller can be driven with temperatures around 90 degrees Celsius. This can be generated with standard flat plate solar collectors. Different systems have been designed and tested, but their economics turned out to be poor. As a result this field of applications has been disregarded over the last 10 years. Recently some newer cooling cycles have become available, the solar collector performance has improved, and collector prices have gone down. So solar cooling may become a feasible option (Henning, 1999).

Solar cooking. About half the world’s cooking uses firewood as the fuel, with the other half based on gas, kerosene, or electricity. In some regions cooking energy requirements place a great pressure on biomass resources while also causing considerable inconvenience and health effects to users in the collection and burning of biomass (see chapter 3). Considering that these regions also have significant levels of solar radiation, it would appear that cooking provides a significant and beneficial impact.

China and India are among several countries promoting the use of solar cookers. A simple box-type cooker and a parabolic concentrating type cooker are among the common models deployed. Efforts have also been made to develop solar cookers for institutional use. In India some 450,000 box type cookers have been installed. The world’s largest solar cooking system - capable of preparing meals for 10,000 persons twice a day - was installed in 1999 in Taleti in Rajasthan, India (TERI, 1996/97; MNCES, 1999). In China some 100,000 concentrator-type cookers have been deployed (Wentzel, 1995).

Solar cooking devices have certain limitations and can only supplement, not replace conventional fuels. A home that uses a solar cooker regularly can save a third to a half of the conventional fuel that is used for cooking. The economic payback time is usually between 2 - 4 years. The large-scale use of solar cookers, however, will also require some adjustment by users.

Solar crop drying. The drying of agricultural products requires large quantities of low-temperature heat - in many cases, year round. Low-cost air-based solar collectors can provide this heat at collection efficiencies of 30 - 70 percent (Voskens and Carpenter, 1999). In Finland, Norway, and Switzerland hay drying is already an established technology. By 1998 more than 100,000 square metres of air collectors for drying purposes had been installed.

In developing countries 60 - 70 percent of grain production (as estimated by the Food and

Agriculture Organisation) is retained at the farmer level, and crop drying is effected predominantly by exposure to direct sunlight (sun drying). In industrialised countries crops are typically dried in large fossil-fuelled drying systems, operating at relatively high temperatures with a high throughput of material. If a solar dryer is used in place of sun drying, there will not be any energy savings, but the solar dryer will achieve higher throughput of material, better quality of material, and lower loss of material (to pests or theft). Air-collector-type solar dryers have the most potential in replacing fuel-fired dryers for crops dried at temperatures less than 50 degrees Celsius (table 7.17).

TABLE 7.17. WORLD PRACTICAL POTENTIAL ESTIMATION FOR SOLAR CROP DRYING (PETAJOULES A YEAR)

Type of drying	**Low**	**High**
< 50 degrees Celsius	220	770
> 50 degrees Celsius	40	110
Sun dried	420	650
Total	**680**	**1,530**

Source: ESIF, 1996; Voskens and Carpenter, 1999.

The technology for solar crop drying is available, and its application can be economically viable. Market introduction of these technologies will thus be the next step, but that will require training and demonstration projects targeted at specific crops and specific potential users and regions.

Passive solar energy use. The application of passive solar principles can contribute significantly to the reduction of (active) energy demands for heating, cooling, lighting, and ventilating buildings. Some of these principles (Boyle, 1996) are:

- Be well insulated.
- Have a responsive, efficient heating system.
- Face south.
- Avoid overshading by other buildings.
- Be thermally massive.

The principles have to be considered in relation to the building design process, because they have a direct effect on the architectural appearance of the building, on the level of comfort (heat, cold, light, ventilation), and on people’s experience of the building. Nowadays a number of techniques can diminish energy demands with passive means:

- *Low-emission double-glazed windows.* In cold climates these windows keep out the cold while allowing the solar radiation to pass. In summer the windows can be shaded, and heat is kept outside.

- *Low-cost opaque insulation material and high insulating building elements.* These elements can keep out the heat as well as the cold.

- *Transparent insulation material.* This material can be used to allow day-lighting while keeping out the cold or heat.

- *High-efficiency ventilation heat recovery.*

- *High-efficiency lighting systems and electrical appliances with automatic control.* These can bring down the internal heat gain, reducing the cooling load. Advanced daylight systems can lead to 40 percent reduction of the energy use for lighting purposes.

By carrying out detailed simulation studies, the energy demand of a building can be optimised, without affecting comfort (Hastings, 1994). It has been estimated that 13

percent of the heat demand of buildings is covered by passive solar energy use. For optimised buildings this fraction can go up to 30 percent without major investments (Brouwer and Bosselaar, 1999). Because of the development of better materials and powerful simulation models, passive use of solar energy is becoming the number one consideration for heating and cooling buildings.

Implementation issues

In many countries incentive programmes help to stimulate the further development and application of low-temperature solar energy systems, improving their performance and reducing economic and other barriers. In countries where government stimulation is lacking, it is often the economic attractiveness of the system or environmental conscience that motivates people to install these systems.

In many cases energy companies, especially utilities, have stimulated the use of solar thermal energy. Motivated by environmental action programs, demand-side management programs, or a desire to diversify and serve new markets, these companies have taken over a significant part of the effort to get the solar water systems to the market. They support these projects by active marketing, by financial contributions, or by offering the possibility to rent or lease a system (IEA Caddet, 1998).

Conclusion

- **Low-temperature solar thermal technologies can contribute many exajoules to the annual heat demand. Today this contribution is limited to about 50 petajoules a year (excluding heat pumps and passive solar energy use).**

- **World-wide, about 7 million solar hot water systems, mainly SDHW systems, have been installed. In many regions their dissemination strongly depends on governmental policy, mainly because of the relatively high heat-production costs**

($0.03 - 0.20 a kilowatt hour). They can, however, compete with electric hot water systems.

- **The costs of installed solar hot water systems in moderate climate zones may be reduced 25 - 50 percent by further technology development and/or mass production and installation.**

- **Active solar systems for space heating with seasonal storage are mainly in a demonstration phase.**

- **Passive solar energy use has become an attractive option in heating and cooling buildings, because of the development of new materials and powerful simulation tools.**

- **Electric heat pumps for space heating are especially attractive in countries where electricity is produced by hydropower or wind energy. In other countries a net contribution to the energy supply is achieved only if they have a high performance factor.**

- **Solar drying of agricultural crops is in many cases a viable technological and economical option. The next step is market introduction.**

- **Solar cooking provides a significant beneficial impact. Many hundreds of thousands of solar cooking devices have been sold, but they have limitations and can only supplement conventional fuel use.**

Hydroelectricity

There is a general view that hydroelectricity is the renewable energy source par excellence, non-exhaustible, non-polluting, and more economically attractive than other

options. And although the number of hydropower plants that can be built is finite, only a third of the sites quantified as economically feasible are tapped.

Hydropower plants emit much less greenhouse gas than do thermal plants. Greenhouse gas emissions of hydropower are caused by the decay of vegetation in flooded areas and by the extensive use of cement in the dam construction. Unfortunately, there are local impacts of the use of rivers, social as well as ecological, and they are gaining importance as people become aware of how those impacts affect living standards.

Most renewable sources of energy hydroelectricity generation are capital intensive but have lower operational costs than thermal and nuclear options. The high initial cost is a serious barrier for its growth in developing countries where most of the untapped economic potential is located.

The potential of hydroelectricity

Chapter 5 provides extensive information on the theoretical and technical potential of hydroelectricity. An overview is given in table 7.18, which also presents the economically feasible potential, estimated at 8,100 terawatt-hours a year.

In 1997 total installed hydroelectric capacity was about 660 gigawatts, of which about 23 gigawatts were small scale (plant capacity of less than 10 megawatts). About a fifth of the world electricity supply, hydroelectricity produced 2,600 terawatt-hours (*World Atlas,* 1998), of which about 3.5 percent (about 90 terawatt-hours) was in small hydroelectric plants.

In some regions (North America, Western Europe, Pacific OECD countries) more than 65 percent of the economically feasible potential is already in use. In others (Sub-Saharan Africa, centrally planned Asia, India) less than 18 percent of the potential is in use (see table 7.18). In Latin America and the Caribbean nearly 44 percent of the economically

feasible potential is already tapped. Since the OECD operational capacity is at 80 percent of the economic potential, most experts believe this value to be an upper limit for capacity installation.

In 1997 the hydro capacity under installation was 125 gigawatts. Assuming these plants will have the same average capacity factor as the units already in operation (45 percent), this represents another 490 terawatt-hours a year, or 6 percent of the economically feasible potential. This will push the hydroelectricity production in the first years of the 21st century to at least 3,000 terawatt-hours a year. By the middle of this century that could grow to 6,000 terawatt-hours a year (IIASA and WEC, 1998; Johansson and others, 1993a).

In 1997 developing countries had a total installed capacity of 262 gigawatts, soon to grow to about 364 gigawatts (see table 7.18). In 1997 the 70 major developing countries were responsible for 225 gigawatts of installed capacity (*World Atlas,* 1998). In 1989 - 97 these 70 countries' installed capacity increased by 40 gigawatts, or about 22 percent (2.5 percent a year),[2] much less than the 5.7 percent a year growth forecast by Moore and Smith (1990). The significant slowdown in the construction of hydroelectric plants in developing countries, compared with 1970 - 90 (Moore and Smith, 1990; Churchill, 1994), can mainly be explained by shortages of capital and difficulties in finding financing abroad.

Hydroelectric technology development

Technologies to reduce dam construction and power generation costs. Hydroelectricity generation is usually regarded as a mature technology, unlikely to advance. That may be so for the efficiency and cost of conventional turbines, where the large number of units constructed has led to an optimised design. But for small-scale hydropower, there is room for further technical development. Examples include the use of variable speed turbines at low heads, induction generators, electronic control and telemetry, submersible turbo-

generators, new materials, and the further development of innovative turbines (EUREC Agency, 1996; Schainker, 1997).

On dam construction, there has recently been further progress, especially with roller compacted concrete (RCC) dams. The lower cement content and the mechanised placing of the concrete yield a relatively low unit cost of around $30 - 40 per cubic metre of dam body, less than half the price of conventional placed concrete. Due to the rapid concrete placement with the RCC technique, dams can grow by 60 centimetres a day, making it possible to build a 200-metre high dam in less than a year (Oud and Muir, 1997). With RCC dams, river diversion during construction is often in-river, rather than by diversion tunnels, saving time and money. The RCC technology has made many dams feasible that previously appeared economically unattractive (Oud and Muir, 1997). For smaller structures, dams with geo-membrane lining (up to 80 metres high) and inflatable rubber weirs (up to 15 metres high) are becoming acceptable alternatives to concrete weirs and low rock-fill or earth-fill dams.

Other parts of the operational system, such as spillways, are now better understood, allowing the use of higher specific discharges per meter width of the spillway chute, saving on cost (Oud and Muir, 1997). Tunnel-boring machines are becoming more attractive. Underground water conduits are attractive because they do not disturb the landscape (Oud and Muir, 1997). Power houses and control rooms are being designed to cut costs and manufacturing time of hydroelectric equipment.

The present installed system cost ranges from $1,000 - 1,500 a kilowatt for the most favourable sites. In practice cost figures of $3,000 a kilowatt and higher are also found. There are some expectations that technology advances can reduce costs, but in small amounts since the present technology is well optimised. With low investment costs and favourable financing conditions (interest 6 percent a year and 30 years for payment), generation costs for an average capacityfactor of 45 percent is $0.04 - 0.06 a kilowatt

hour. At higher capacity factors and with longer payback times, lowest generations costs of about $0.02 a kilowatt hour are found. Because the plant is usually placed far from the point of electricity use, investment can also be required for transmission, perhaps adding another $0.01 per kilowatt-hour.

For small-scale hydropower, the unit cost is expected to be higher than for large-scale hydro. But with the choice of very favourable sites, the use of existing administrative structures and existing civil works for flood-control purposes, avoiding the use of cofferdams during installation, and refurbishing of old sites, electricity production costs may come down from $0.04 - 0.10 a kilowatt-hour to $0.03 - 0.10 a kilowatt-hour.

Technologies to reduce social and ecological impacts. Considering the criticism of hydropower production, especially when large dams are built, modern construction tries to include in the system design several technologies that minimise the social and ecological impacts. Some of the most important impacts are changes in fish amount and fish biodiversity, sedimentation, biodiversity perturbation, water quality standards, human health deterioration, and downstream impacts (see also chapter 3).

Only a third of the sites quantified as economically feasible for hydro-electricity production are tapped.

- ***Changes in fish amount and fish biodiversity.* Technologies are being pursued to preserve subsistence and commercial fish production as well as fish biodiversity. Further R & D is being recommended to achieve a quantitative understanding of the responsesof fish to multiple stresses inside a turbine and to develop biological performance criteria for use in advanced turbine design (National Laboratory,**

1997). Inclusion of passage facilities, such as fish ladders (Goodland, 1997), are becoming a necessity for renewing dam operational contracts in the United States. In tropical countries, where such technology is not useful, electric luring of fish into containers or elevators, as carried out in Yacyreta(between Argentina and Paraguay), may be a solution (Goodland, 1997). Because most new dams will be built in tropical countries, it is necessary to carry out extensive studies to identify new or rare species and determine if they can live in adjacent rivers not slated for damming (Goodland, 1997).

- ***Sedimentation.*** **Sedimentation increases strongly when catchments are developed. Another possibility is the sporadic filling of the reservoir with large amount of land due to land slide or due to some exceptional flood (Goodland, 1997). Such problems can be minimised through watershed management, debris dams, sediment bypassing, sediment flushing, sediment sluicing, sediment dredging, and using reservoir density currents.**

- ***Biodiversity perturbation.*** **Conservation of biodiversity demands, at the least, no net loss of species. This requires complete knowledge of what is present before the dam is built, which is difficult. The main conservation measures have become site selection and selection of reservoir size. In practice, the conservation of onsite biodiversity depends on not flooding large areas, particularly intact habitats such as tropical forests, and on conserving an offset in perpetuity (Goodland, 1997).**

- ***Water quality.*** **Initially water quality is mainly disturbed by the large amount of biomass left in the flooded area and by filling the reservoir. This can be mitigated by removing biomass and by fillingthe reservoir at a moderate rate. After filling, thermal stratification frequently occurs in reservoirs with a long water residence time (full seasons cycle) and water depths of more than 10 metres. Reservoir stratification can release water of colder or warmer temperatures than the river**

would experience without a dam, with positive or negative impacts on the river fishery. It can be minimised through (1) changes in inlet structure configuration, (2) in-reservoir de-stratification, (3) multilevel outlet works for mitigation of downstream effects, and (4) positive mixing and aeration by fountain jets or compressed air. But sufficient knowledge is not yet available, and further R&D is recommended (National Laboratory, 1997).

- ***Human health deterioration.*** **Reservoirs can cause epidemics of three water-related diseases: malaria, schistosomiasis, and Japanese B encephalitis. The proliferation of malaria and encephalitis can be avoided with chemicals and chemotherapy. But resistance ofmosquitoes and *Plasmodium* protozoan parasite makes malaria increasingly expensive to control. Schistosomiasis is better controlled by chemotherapy.**

- ***Downstream impacts.*** **Downstream social impacts can exceed upstream resettlement upheavals, and they deserve more attention than is common nowadays. Cessation of annual fertile silt and moisture deposition leads to declining yields, grazing impairment, fish and wildlife decline, and erosion at the mouth of the river, due to the reduction in suspended particles that replace the land normally washed out by the ocean. In addition, the decline in water availability and agricultural yields increases the competition for water and other scarce resources. Furthermore, the construction of a dam forces people who are long adapted to cyclical floods to switch suddenly to rainfed livelihoods (Goodland, 1997). Some of these issues can be mitigated through off-takes at various levels to allow for flexibility of the water temperature in accord with downstream needs, and others through measures that reduce reservoir stratification, including local mixing and shorter water residence time.**

System aspects

To even out annual seasonal flow, dams are erected and land areas flooded. Since the flows vary from year to year, every attempt to increase the reliability of the water supply increases the flooded area, and that increase is exponential for reliability above 70 percent (Moreira and Poole, 1993). Another alternative to increase system reliability and reduce cost is hydropower complementation, based on the notion that different river basins can be wire connected, letting a higher flow in one basin compensate for low flow in the other. Hydrologic diversity usually involves large geographic distance, but on either side of the equator distances are modest (Moreira and Poole, 1993).

A third alternative is to use hydroelectricity to store intermittent renewable energy. Storage energy, to ensure reliable, high quality service, will provide for increased renewable use and system stabilisation with distributed generation. Areas of importance include pumped hydro (Schainker, 1997). Further research is recommended to examine the benefits and costs of coupling hydropower to renewable energy storage needs (PCAST, 1997).

TABLE 7.18. HYDROELECTRIC THEORETICAL, TECHNICALLY FEASIBLE, AND ECONOMICALLY FEASIBLE POTENTIAL AS WELL AS INSTALLED AND UNDER INSTALLATION CAPACITY IN 1997, BY REGION (TERAWATT-HOURS A YEAR UNLESS OTHERWISE NOTED)

Region	Gross theoretical potential	Technically feasible potential	Economically feasible potential	Installed hydro capacity (gigawatts)	Installed hydro capacity in developing countries (gigawatts)	Production from hydro plants	Hydro capacity under constructio (gigawatts

North America	5,817	1,509	912	141.2	0	697	0
Latin America and Caribbean	7,533	2,868	1,199	114.1	114.1	519	18
Western Europe	3,294	1,822	809	16.3	16.3	48	2
Central and Eastern Europe	195	216	128	9.1	9.1	27	7
Former Soviet Union	3,258	1,235	770	146.6	16.5	498	6
Middle East and North Africa	304	171	128	21.3	0	66	1
Sub-Saharan Africa	3,583	1,992	1,288	65.7	0	225	16
Centrally planned Asia	6,511	2,159	1,302	64.3	64.3	226	51
South	3,635	948	103	28.5	28.5	105	13

Asia[a]							
Pacific Asia[a]	5,520	814	142	13.5	13.5	41	4
Pacific OECD	1,134	211	184	34.2	0	129	0
World total	**40,784**	**13,945**	**6,965**	**654.8**	**262.3**	**2,581**	124
World total[b]	**~40,500**	**~14,320**	**~8,100**	**~660**		**~2,600**	**~12**

a. Several South Asian and other Pacific Asian countries do not release their economically feasible potential. As a result economically feasible potential for these regions are too low, and in one case for South Asia are even lower than the electricity generated. b. These are the values quoted in the source. They differ from the world total in the previous row mainly due the inclusion of estimates for countries for which data are not available.

Source: World Atlas, 1998.

Environmental and social impacts

The average energy density of hydroelectricity generation shows thatt significant amounts of land have been flooded for this purpose (see chapter 5). If new plants will keep the average energy density (optimistic, since the best sites have already been used), some extra 50 million hectares of land will be flooded to make available two-thirds of the economic potential. This figure may not look so high relative to the land required for biomass energy production, but river surroundings are the most densely inhabited areas in

rural regions. Several other environmental impacts in the flooded area can be minimised by convenient choosing of sites where it is possible to store large water volumes in a small area, such as canyons.

With a responsibility to preserve the environment, the overall cost of producing hydropower is increasing. As the hydropower industry moves towards an open market, it is a challenge to figure out how it will survive marginal cost pricing. Some operators with high costs could also find themselves in a restructured environment with old and insufficient generating plant. In the United States several dams associated with power production are being decommissioned, mainly because they disturb commercial fishing or impose a significant onus for biodiversity (Koch, 1996).

A well-understood impact is caused by displacing inhabitants from the flooded area, and mitigating it can represent a significant cost for the project. Some estimates put the displacement cost per person at about six times the annual per capita gross national product (Besant-Jones, 1995) - and others as high as $25,000 per family. Displacing 100,000 inhabitants can add $2 billion to the project cost, enough to make it unfeasible. Strong criticism is always to be expected for hydro projects requiring the relocation of a great number of people. Of utmost importance here is building trust between the people affected by resettlement, the developer, and the authorities; people must know and feel that they matter and that they are taken seriously.

Economic and financial aspects

Hydropower plants are more capital intensive than thermal plants. Historically, hydroelectricity in the developing world has been financed predominantly from public or guaranteed funding. The World Bank has financed about 110 hydroelectric power projects in 50 developing countries, ranging from 6.6 megawatts to 2,240 megawatts, with a combined generating capacity of about 35 gigawatts. Reliable global data on trends in

hydro financing are not available. But World Bank data show a market decline in its lending for hydro - from 3.4 percent to 2.5 percent of the approximately $20 billion it lends annually. There is no doubt that environmental pressures on the Bank (and other multilateral agencies) account for some of this decline (Briscoe, 1998).

In the past few years with the emerging privatisation of the electric sector in developing countries, private capital flows have increased dramatically (Briscoe, 1998). Private activity in infrastructure, previously concentrated in East Asia and Latin America, is now expanding in Eastern Europe and Central Asia, South Asia, and Sub-Saharan Africa. Private infrastructure investment can grow much more, since it accounted for only about 15 percent of all infrastructure investment in developing countries in 1996. Even so, the private sector sees substantial risks, some inherent in the degree to which each hydro project (unlike thermal projects) has to be tailored to specific hydrological, geographic, and geological conditions.

Modern construction of dams tries to include technologies that minimize the social and ecological impacts.

In addition, hydropower project costs have tended to exceed estimates substantially. A World Bank review of 80 hydro projects completed in the 1970s and 1980s indicate that three-fourths had final costs in excess of budget. Costs were at least 25 percent higher for half the projects and 50 percent or more for 30 percent of the projects. Costs were less than estimated on 25 percent of projects (Bacon and others, 1996). Major reasons for such cost increases were unexpected geologic conditions, funding delays, and resettlement problems (Churchill, 1997).

It is essential that the hydro industry comes to grips with the poor record of cost estimation and project implementation. This record has caused the financial community to regard hydro project as riskier than in the past, raising the cost of capital and pricing many hydro projects out of the market. Inadequate resource exploration and site investigation is one reason for the cost and schedule overruns. Governments can solve this by initiating careful resource and site investigations at an early stage using public money. They can recover these costs from the project developer as part of an authorisation or tendering procedure.

It is much easier to involve the private sector in smaller projects, of 40 - 400 megawatts, where hydropower plants are accepted as environmentally benign if they are run-of-the river, incorporate high head, and are on tributaries to the big rivers (Briscoe, 1998). For larger projects there has been, and will be, little private sector financing unless there is substantial involvement of governments and bilateral and multilateral agencies (Briscoe, 1998).

Conclusion

- **Hydropower contributes about 20 percent to the electricity supply, about a third of its potential. The supply of hydroelectricity may grow from 2,600 terawatt-hours a year in 1997 (of which about 3.5 percent from small-scale hydropower) to 3,000 terawatt-hours in the first years of the 21st century and to 6,000 ter-awatt-hours a year in 2050.**

- **Hydropower is a clean energy source with many technical advantages over thermal and nuclear plants: operating reserves, spinning reserves, load following services, voltage control, and cold start capability. Some of these characteristics help in aggregating intermittent sources of electricity to the existing system.**

- **The electricity production cost of large hydroelectricity plants is $0.02 - 0.08 a**

kilowatt-hour, with new reductions from technology development offset by the need to mitigate social and environmental effects. For small hydroelectricity plants, the electricity production cost may come down from $0.03 - 0.10 a kilowatt-hour to $0.04 - 0.10 a kilowatts-hour in the long term.

- **Improvements and efficiency measures are needed in dam structures, turbines, generators, substations, transmission lines, and environmental mitigation technology to sustain hydropower's role as a clean, renewable energy source. Of utmost importance is building trust between the people affected by resettlement, the developer and the authorities - to address the criticisms regarding social and environmental impacts.**

- **The emerging liberalisation and privatisation in the electric sector in most industrialised countries may reduce investments in new hydropower plants since they are more capital intensive and riskier than thermal plants.**

Geothermal energy

Geothermal energy has been used for bathing and washing for thousands of years, but it is only in the 20th century that it has been harnessed on a large scale for space heating, industrial energy use, and electricity production. Prince Piero Ginori Conti initiated electric power generation with geothermal steam at Larderello in Italy in 1904. The first large municipal district heating service started in Iceland in the 1930s.

Geothermal energy has been used commercially for some 70 years, and on the scale of hundreds of megawatts, 40 years, both for electricity generation and direct use. Its use has increased rapidly in the past three decades - at about 9 percent a year in 1975 - 95 for electricity and at about 6 percent a year for direct use. Geothermal resources have been identified in more than 80 countries, with quantified records of geothermal use in 46.

The potential of geothermal energy

Exploitable geothermal systems occur in several geological environments. High-temperature fields used for conventional power production (with temperatures above 150° C) are largely confined to areas with young volcanism, seismic, and magmatic activity. But low-temperature resources suitable for direct use can be found in most countries. The ground source heat pump has opened a new dimension in using the Earth's heat, as these pumps can be used basically everywhere.

Geothermal use is commonly divided into two categories - electricity production and direct application. In 1997 world-wide use of geothermal energy amounted to about 44 terawatt-hours a year of electricity and 38 terawatt-hours a year for direct use (table 7.19). A new estimate of world geothermal potential shows the useful accessible resource base for electricity production to be some 12,000 terawatt-hours a year (Bjrnsson and others, 1998). Since only a small fraction of the geothermal potential has been developed, there is ample space for accelerated use of geothermal energy for electricity generation in the near future.

The scope for direct use of geothermal energy is even more plentiful, as the useful accessible resource base is estimated to be 600,000 exajoules, which corresponds to the present direct use of geothermal energy for some 5 million years (Bjrnsson and others, 1998). With both ample resources and a relatively mature technology at hand, the question of future development of geothermal energy use boils down to economic and political competitiveness with other energy sources on the markets in different countries.

Recent developments

Electricity production. The growth of the total generation capacity in 1990 - 98 was about 40 percent (table 7.20), with the largest additions in the Philippines (957 megawatts), Indonesia (445 megawatts), Japan(315 megawatts), Italy (224 megawatts), Costa Rica

(120 megawatts), Iceland (95 megawatts), theUnited States (75 megawatts), New Zealand (62 megawatts), and Mexico (43 megawatts). The most progressive of these countries, the Philippines, with 22 percent of its electricity generated with geothermal steam, plans to add 580 megawatts to its installed capacity in 1999 - 2008 (Benito, 1998). Other countries generating 10 - 20 percent of their electricity with geothermal are Costa Rica, El Salvador, Kenya, and Nicaragua.

TABLE 7.19. ELECTRICITY GENERATION AND DIRECT USE OF GEOTHERMAL ENERGY, 1997

Region	Electricity generation			Direct use		
	Installed capacity (gigawatts-electric)	Total production		Installed capacity (gigawatts-thermal)	Total production	
		Terawatt-hours (electric)	Percent		Terawatt-hours (thermal)	Percent
European Union	0.75	3.8		1.03	3.7	
Europe, other	0.11	0.5		4.09	16.1	
Total Europe	0.86	4.3	10	5.12	19.8	52
North America	2.85	16.2		1.91	4.0	
Latin America	0.96	6.9				
Total	3.81	23.1	53	1.91	4.0	10

Americas						
Asia	2.94	13.0	30	3.08	12.2	32
Oceania	0.36	2.9	6	0.26	1.8	5
Africa	0.05	0.4	1	0.07	0.4	1
World total	**8.02**	**43.8**	**100**	**10.44**	**38.2**	**100**

Source: Based on Stefansson and Fridleifsson, 1998.

TABLE 7.20. INSTALLED GEOTHERMAL ELECTRICITY GENERATION CAPACITY (MEGAWATTS OF ELECTRICITY)

Country	1990	1995	1998
Argentina	0.7	0.7	0
Australia	0	0.2	0.4
China	19	29	32
Costa Rica	0	55	120
El Salvador	95	105	105
France (Guadeloupe)	4	4	4
Guatemala	0	0	5
Iceland	45	50	140
Indonesia	145	310	590
Italy	545	632	769
Japan	215	414	530
Kenya	45	45	45

Mexico	700	753	743
New Zealand	283	286	345
Nicaragua	70	70	70
Philippines	891	1,191	1,848
Portugal (Azores)	3	5	11
Russia	11	11	11
Thailand	0.3	0.3	0.3
Turkey	20	20	20
United States	2,775	2,817	2,850
Total	**5,867**	**6,798**	**8,239**

Source: Based on IGA, 1999.

The participation of private operators in steam field developments through BOT (build, operate, and transfer) and BOO (build, own, and operate) contracts and through JOC (joint operation contracts) have significantly increased the speed of geothermal development in the Philippines (Vasquez and Javellana, 1997) and Indonesia (Radja, 1997; Aryawijaya, 1997). And several developing countries are considering the participation of private operators.

The electricity generation cost is variable - commonly around $0.04 a kilowatt-hour for modern, cost-effective plants, but ranging from $0.02 - 0.10 a kilowatt-hour. The installed system costs may range from $800 - 3,000 a kilowatt-hour. With cost reductions and under favourable conditions the cost can come down to $0.01 - 0.02 a kilowatt-hour.

Direct use of geothermal energy. Direct application of geothermal energy can involve a wide variety of end uses, such as space heating and cooling, industry, greenhouses, fish

farming, and health spas. It uses mostly existing technology and straightforward engineering. The technology, reliability, economics, and environmental acceptability of direct use of geothermal energy have been demonstrated throughout the world.

Compared with electricity production from geothermal energy, direct use has several advantages, such as much higher energy efficiency (50 - 70 percent compared with 5 - 20 percent for conventional geothermal electric plants). Generally the development time is much shorter, and normally much less capital investment is involved. And possible for high- and low-temperature geothermal resources, direct use is much more widely available in the world. But it is more site specific for the market, with steam and hot water rarely transported long distances from the geothermal site. The longest geothermal hot water pipeline in the world, in Iceland, is 63 kilometres.

The production costs for direct use are highly variable, but commonly under $0.02 a kilowatt-hour. The production costs might range from $0.005 - 0.05 a kilowatt-hour (thermal energy), and the turnkey investments costs from $200 - 2,000 a kilowatt.

The two countries with the highest energy production (Japan and Iceland) are not the same as the two with the highest installed capacities (China and the United States), because of the variety in the load factors for the different types of use (table 7.21).

Lund (1996) has recently written a comprehensive summary on the various types of direct use of geothermal energy. Space heating is the dominant application (33 percent). Other common applications are bathing/swimming/balneology (19 percent), greenhouses (14 percent), heat pumps for air conditioning and heating (12 percent), fish farming (11 percent), and industry (10 percent).

Heat pump applications. Geothermal energy previously had considerable economic potential only in areas where thermal water or steam is found concentrated at depths less than 3 kilometres, analogous to oil in commercial oil reservoirs. This has changed recently

with developments in the application of ground source heat pumps - using the Earth as a heat source for heating or as a heat sink for cooling, depending on the season. These pumps can be used basically everywhere.

Switzerland, not known for hot springs and geysers, shows the impact geothermal heat pumps can have - generating about 230 gigawatt-hours a year in 1994 (Rybach and Goran, 1995). In the United States, at the end of 1997, more than 300,000 geothermal heat pumps were operating nation-wide in homes, schools, and commercial buildings for space heating and cooling (air conditioning), providing 8 - 11 terawatt-hours a year of end-use energy according to different estimates.

Geothermal heat pumps are rated among the most energy-efficient space conditioning equipment available in the United States. Reducing the need for new generating capacity, they perform at greater efficiencies than conventional air source heat pumps used for air conditioning. Several electric utilities have introduced financial incentive schemes by encouraging house owners to use groundwater heat pumps for space cooling and heating purposes and thus reducing the peak loads on their electric systems. The Geothermal Heat Pump Consortium has established a $100 million 6-year program to increase the geothermal heat pump unit sales from 40,000 to 400,000 annually, which will reduce greenhouse gas emissions by 1.5 million metric tonnes of carbon equivalent annually (Pratsch, 1996). A third of the funding comes from the U.S. Department of Energy and the Environmental Protection Agency, two-thirds from the electric power industry. Financial incentive schemes have also been set up in Germany and Switzerland.

Potential market developments

Some 80 countries are interested in geothermal energy development, of which almost 50 now have quantifiable geothermal use. A worldwide survey (Fridleifsson and Freeston, 1994) showed that the total investments in geothermal energy in 1973 - 92 were about

$22 billion. In 1973 - 82 public funding amounted to $4.6 billion, private funding to $3 billion. In 1983 - 92 public funding amounted to $6.6 billion, private funding to $7.7 billion. Of special interest, private investment in geothermal rose by 160 percent from the first decade to the second, while public investments rose by 43 percent, showing the confidence of private enterprises in this energy source and demonstrating its commercial viability.

Extrapolations of past trends show the long-term prognosis for potential development. In 1975 - 95 the growth of the installed capacity for electricity generation world-wide was about 9 percent a year. If this rate continues for another 25 years, the installed capacity would be 25 gigawatts of electricity in 2010 and 58 gigawatts of electricity in 2020 (table 7.22). The annual electricity generation shown in table 7.22 is based on the assumption that the use factor will be similar to that in 1997 (Stefansson and Fridleifsson, 1998). In 1990 - 98 the annual growth was close to 4 percent a year, not 9 percent. So, new incentives are needed to realise this scenario.

The average growth in the direct use of geothermal energy can be estimated at about 6 percent a year in the past decade. With annual growth rate of 6 percent in the near future, the installed capacity would be around 22 gigawatts of thermal energy in 2010 and 40 gigawatts of thermal energy in 2020 (see table 7.22). This is not taking into account the rapid development of ground-based heat pumps in recent years. In a matter of some years, this sector has grown from infancy to 1,400 megawatts of thermal energy in the United States alone. Development is also fast in Switzerland, Germany, and Sweden. The forecast for direct use therefore might be somewhat pessimistic.

The U.S. Department of Energy’s Office of Geothermal Technologies recently identified five strategic goals for geothermal energy as a preferred alternative to polluting energy sources (USDOE OGT, 1998), including:

- **Supply the electric power needs of 7 million U.S. homes (18 million people) fromgeothermal energy by 2010.**

- **Expand direct uses of geothermal resources and applicationof geothermal heat pumps to provide the heating, cooling, and hot water needs of 7 million homes by 2010.**

- **Meet the basic energy needs of 100 million people in developing countries by using U.S. geothermal technology to install at least 10 gigawatts by 2010.**

TABLE 7.21. GEOTHERMAL ENERGY PRODUCTION WITH DIRECT USE IN COUNTRIES WITH MORE THAN 40 MEGAWATTS-THERMAL INSTALLED CAPACITY

Country	Installed capacity (gigawatts-thermal)	Heat production (terawatt-hours a year)
Japan	1.16	7.50
Iceland	1.44	5.88
China	1.91	4.72
United States	1.91	3.97
Hungary	0.75	3.29
Turkey	0.64	2.50
New Zealand	0.26	1.84
France	0.31	1.36
Italy	0.31	1.03
Germany	0.31	0.81
Georgia	0.25	n.a

Serbia	0.09	0.67
Russia	0.21	0.67
Romania	0.14	0.53
Switzerland	0.19	0.42
Slovak Rep.	0.08	0.38
Sweden	0.05	0.35
Tunisia	0.07	0.35
Bulgaria	0.10	0.35
Israel	0.04	0.33
Macedonia FYR	0.08	0.15
Poland	0.04	0.14

Source: Based on Stefansson and Fridleifsson, 1998.

TABLE 7.22. POTENTIAL DEVELOPMENT OF THE INSTALLED CAPACITY AND ENERGY PRODUCTION FROM GEOTHERMAL SOURCES IN THE FORM OF ELECTRICITY AND DIRECT USE OF HEAT, 1997 - 2020

Year	Gigawatts - electric	Terawatt- hours (electric)	Gigawatts- electric	Terawatt- hours (thermal)
1997	8.0	43.8	10.4	38.20
2010	24	134	22	81
2020	58	318	40	146

Environmental aspects

Geothermal fluids contain a variable quantity of gas - largely nitrogen and carbon dioxide with some hydrogen sulphide and smaller proportions of ammonia, mercury, radon, and boron. The amounts depend on the geological conditions of different fields. Most of the chemicals are concentrated in the disposal water, routinely re-injected into drill holes, and thus not released into the environment. The concentrations of the gases are usually not harmful, and the removal of such gases as hydrogen sulphide from geothermal steam is a routine matter in geothermal power stations where the gas content is high. The range in carbon dioxide emissions from high-temperature geothermal fields used for electricity production in the world is 13 - 380 grams a kilowatt-hour, less than for fossil fuel power stations. Sulphur emissions are also significantly less for geothermal than fossil fuel electric power stations.

The gas emissions from low-temperature geothermal resources are normally only a fraction of the emissions from the high-temperature fields used for electricity production. The gas content of low-temperature water is in many cases minute - in Reykjavik, Iceland, the carbon dioxide content is lower than that of the cold groundwater. In sedimentary basins, such as the Paris basin, the gas content may be too high to be released. In such cases the geothermal fluid is kept at pressure within a closed circuit (the geothermal doublet) and re-injected into the reservoir without any degassing. Conventional geothermal schemes in sedimentary basins commonly produce brines that are generally re-injected into the reservoir and thus never released into the environment. The carbon dioxide emission from these is thus zero.

Conclusion

- **Geothermal energy has been used commercially for 70 years, both for electricity generation and direct use, with use increasing rapidly in the past three decades. In 1975 - 95 the growth rate for electricity generation was about 9 percent a year and in recent years about 4 percent a year. For direct use it was about 6 percent a year.**

- **For the 46 countries with records of geothermal use the electricity generated was 44 terawatt-hours of electricity and the direct use 38 terawatt-hours of thermal energy in 1997, and 45 terawatt-hours of electricity and 40 terawatt-hours of thermal energy in 1998.**

- **Assuming world-wide annual growth to average 9 percent a year through 2020, the electricity production may reach about 130 terawatt-hours in 2010 and about 310 terawatt-hours in 2020. Assuming the annual growth rate for direct use to continue at 6 percent, the energy production may reach about 80 terawatt-hours in 2010 and about 140 terawatt-hours in 2020.**

- **Recent developments in the application of the ground source heat pump opens a new dimension in the scope for using the Earth's heat. Heat pumps can be used basically everywhere and are not site-specific, as conventional geothermal resources are.**

- **Geothermal energy, with its proven technology and abundant resources, can make a significant contribution towards reducing the emission of greenhouse gases. But it requires that governments implement policies and measures to improve the competitiveness of geothermal energy systems with conventional energy systems.**

> Not until the 20th century has geothermal energy been harnessed on a large scale for space heating, industrial energy use, and electricity production.

Marine energy technologies

The oceans, covering more than two-thirds of the Earth, represent an enormous energy resource containing vastly more energy than the human race could possibly use. The energy of the seas is stored partly as kinetic energy from the motion of waves and currents and partly as thermal energy from the sun. (Chapter 5 summarises the nature and scale of the ocean energy resource.)

Although most marine energy is too diffuse and too far from where it is needed to be economically exploited, in special situations it can be effectively captured for practical use. Tidal energy needs the more extreme tidal ranges or currents. Wave energy needs to be exploited in places with a higher-than-average wave climate. Ocean thermal energy conversion needs as large a temperature difference as possible between the surface waters and the water near the seabed. Such requirements tend to limit the use of the resource to certain areas of coastline offering the coincidence of a suitably intense resource and a potential market for the energy. This makes many published estimates of enormous global marine energy resources academic.

The potential and technology of marine energy

The main marine energy resources can be summarised, in order of maturity and use, as:

- **Tidal barrage energy.**
- **Wave energy.**
- **Tidal/marine currents.**
- **Ocean thermal energy conversion (OTEC).**
- **Salinity gradient/osmotic energy.**
- **Marine biomass fuels.**

Exploiting salinity gradients and the cultivation of marine biomass are not discussed because their exploitation seems a long way from any practical application, though new research might clarify their potential.

Tidal barrage energy. The rise and fall of the tides creates, in effect, a low-head hydropower system. Tidal energy has been exploited in this way on a small scale for centuries in the form of water mills. The one large modern version is the 240 megawatt-electric La Rance scheme, built in France in the 1960s, the world's largest tidal barrage, using a conventional bulb turbine. A handful of smaller schemes have also been built.

Numerous studies have been completed for potentially promising locations with unusually high tidal ranges, such as the Bay of Fundy in Canada and the 7-gigawatt scheme for the Severn Estuary in the United Kingdom. But most schemes of this kind have proved to be extremely large and costly. The proposed Severn Barrage scheme - which the U.K. government decided not to pursue - would have involved the use of 216 turbo-generators, each nine metres in diameter and 40 megawatts in capacity. The load factor would have been around 23 percent, the cost an estimated $12 billion (Boyle, 1996).

The combination of high costs, major environmental impact, and poor load factors makes this technology generally unattractive, but there may be occasional niche applications for it in the future in especially favourable locations.

Wave energy. Energy can be extracted from waves. As an example, in deep water off the northwest coast of Scotland (one of the more intense wave climates in the world) the average energy along the prevailing wave front can be 70 kilowatts a metre (or more). Closer inshore this falls to an average of around 20 or 30 kilowatts a metre, and along the shoreline to about 10 kilowatts a metre or less. The energy availability is thus sensitive to the distance from the shoreline (ETSU/DTI, 1999).

Wave energy remains at an experimental stage, with only a few prototype systems actually working. All of the few existing systems that have run for more than a few hours are shoreline devices (built into the shore). Total grid-connected wave power is less than 1 megawatt, consisting of several small oscillating water column devices in China, India,

and the United Kingdom (YY, 1998). A new generation of larger devices is under development, due to be installed notably in the Azores (Pico) and Japan, as well as in the countries mentioned earlier. The world's wave energy capacity will increase to a few megawatts in the next few years.

If wave energy is to become an important contributor to future energy needs, it will need to move further offshore into deeper water where there are larger and much more energetic waves. This will require a quantum leap in the size and nature of the systems used. Systems capable of surviving under such difficult conditions have not yet been demonstrated, so it is likely to take a decade or more before wave energy can even start to make a contribution to world energy needs (Fraenkel, 1999). Eventually, however, it seems likely to contribute as much as 100 terawatt-hours a year for Europe, and perhaps three times that for the world.

The general immaturity of wave energy technology is illustrated by the variety of solutions proposed for exploiting it. No real consensus has yet emerged as to the 'best' way to convert energy from waves into electricity. Wave energy conversion systems can be classified as:

- **Shoreline devices (mounted on the shore).**
- **Near-shoreline devices (usually installed on the seabed in water less than 20 metres deep).**
- **Offshore or deep-water devices (usually floating devices moored in deep water with highly energetic wave conditions).**

The most popular shoreline device is the oscillating water column (OWC), a large chamber that has a free opening to the sea, encloses an air volume, and is compressed by the wave pressure. A duct between the chamber and the outside atmosphere allows air to be drawn in and out of the chamber as a result of the variation of pressure caused by incoming

waves. An air-turbine system, installed in the duct, generates electricity from this reversing air flow.

Most near-shore wave energy converters are designed to be deployed in lines parallel to the shoreline to intercept the wave energy. Another concept is the point absorber, which can occupy a small space yet capture the energy from a larger area surrounding it using resonance effects. Studies show that such arrays can be highly efficient (Randlov and others, 1994). In the longer term other large floating devices, such as the Salter Duck, which relies on modules that rock in response to wave action, will convert the higher power levels available farther offshore.

Tidal and marine current energy. Tidal and marine current energy is the most recent of the marine energy resources to be seriously studied, with most work in the 1990s. The results show that large-scale energy generation from currents requires a totally submerged turbine - and, to be reliable, offshore large, robust systems are required that are only now becoming technically feasible.

In most places the movements of seawater are too slow - and the energy availability is too diffuse - to permit practical energy exploitation. But there are locations where the water velocity is speeded up by a reduction in cross-section of the flow area, such as straits between islands and the mainland, around the ends of headlands, and in estuaries and other such topographical features. As with wind energy, a cube law relates instantaneous power to fluid velocity. So a marine current of 2.5 metres a second (5 knots), not an unusual occurrence at such locations, represents a power flux of about 8 kilowatts a square metre. The minimum velocity for practical purposes is around 1 metre a second (2 knots), about 0.5 kilowatts a square metre. The main siting requirement is thus a location having flows exceeding about 1.5 metres a second for a reasonable period (Fraenkel, 1999; IT Power, 1996).

Data on marine currents are sparse. A major study by the European Commission evaluating the tidal current resource for 106 locations around Europe estimated an exploitable resource from just those sites of 48 terawatt-hours a year (IT Power, 1996). The U.K. government recently came up with an estimate of about 320 megawatts of installed capacity for the United Kingdom by 2010 (ETSU/DTI, 1999). There is potential at known United Kingdom locations to install several gigawatts of tidal turbines. The worldwide potential is obviously much larger.

All that has been done so far is the short-term demonstration of small experimental model systems in the sea, the largest so far being only 15 kilowatts, at Loch Linnhe in Scotland in 1994. A Japanese university successfully ran a 3-kilowatt turbine on the seabed off the Japanese coast for some 9 months, and a floating system of about 5 kilowatts was demonstrated in Australian waters. Work is under way to develop and install the first grid-connected tidal current turbine, rated at 300 kilowatts, during 2000.

TABLE 7.23. CURRENT STATUS OF MARINE RENEWABLE ENERGY TECHNOLOGIES

Technology	Maturity	Load factor (percent)	Installed capital cost (dollars per kilowatt)	Unit cost of electricity (dollars per kilowatt-hour)
Tidal barrage	Virtually abandoned	20 - 30	1,700 - 2,500	0.08 - 0.15
Wave - shoreline OWC	Experimental	20 - 30	2,000 - 3,000	0.10 - 0.20
Wave - near shoreline OWC	Commercial 2002 - 05	25 - 35	1,500 - 2,500	0.08 - 0.15
Wave - offshore - point absorber	Commercial 2010 or later	30 - 60	2,500 - 3,000	0.06 - 0.15

Tidal current turbine	Commercial 2005 - 10	25 - 35	2,000 - 3,000	0.08 - 0.15
OTEC	Commercial 2005 - 10	70 - 80	Unclear	Unclear

The various turbine rotor options generally coincide with those used for wind turbines. The two main types are the horizontal axis, axial-flow turbine (with a propeller type of rotor) and the cross-flow or Darrieus turbine, in which blades rotate about an axis perpendicular to the flow. The more promising rotor configuration seems to be the conventional axial flow rotor.

The maximum flow velocity tends to be near the sea’s surface, so marine current turbine rotors ideally need to intercept as much of the depth of flow as possible, but especially the near-surface flow. Options for securing a rotor include mounting it beneath a floating pontoon or buoy, suspending it from a tension leg arrangement between an anchor on the seabed and a flotation unit on the surface, and seabed mounting (feasible in shallow water, but more difficult in deeper water). Floating devices have the problem of providing secure anchors and moorings. Seabed-mounted devices seem more straightforward to engineer. One option is a mono-pile set into a socket drilled into the seabed, which seems the most cost-effective solution, just as it is for offshore wind turbines.

Ocean thermal energy conversion. Exploiting natural temperature differences in the sea by using some form of heat engine, potentially the largest source of renewable energy of all, has been considered and discussed for the best part of 100 years (Boyle, 1996). But the laws of thermodynamics demand as large a temperature difference as possible to deliver a technically feasible and reasonably economic system. OTEC requires a temperature difference of about 20 degrees Celsius, and this limits the application of this technology to a few tropical regions with very deep water. Two main processes are used for power production from this source, both based on the Rankine (steam/vapour) cycle:

- **The open cycle system flash evaporates warm seawater into vapour (at reduced pressure) and then draws it through a turbine by condensing it in a condenser cooled by cold seawater.**

- **The closed cycle system uses warm seawater to boil a low-temperature fluid, such as ammonia, which is then drawn through a turbine by being condensed in a heat exchanger with cold seawater and then recycled back to the boiler by a feed pump.**

Offshore OTEC is technically difficult because of the need to pipe large volumes of water from the seabed to a floating system, the huge areas of heat exchanger needed, and the difficulty of transmitting power from a device floating in deep water to the shore (SERI, 1989). A few experimental OTEC plants have been tested, notably in Hawaii, but do not seem to offer economic viability. Consequently, OTEC is not likely to make a major contribution to the energy supply in the short to medium term. Shoreline OTEC, however, could be more readily developed and applied economically than devices floating in deep waters.

The latest thinking is that OTEC needs to be applied as a multipurpose technology: for example, the nutrient-rich cold water drawn from the deep ocean has been found to be valuable for fish-farming. In addition, the cold water can be used directly for cooling applications in the tropics such as air conditioning (NREL, 1999). If OTEC takes off, it is likely to be with energy as a by-product.

Economic aspects

Because of limited experience with the marine renewables, it is difficult to be certain how economic they will be if developed to a mature stage. There is experience (albeit limited) with tidal barrages, but their failure to take off speaks for itself. A rough indication of the relative unit costs of some offshore technologies is given in table 7.23 (Fraenkel, 1999).

Several of these options are already competitive in the context of niche markets, such as island communities using conventional small-scale diesel generation, which typically can cost from $0.10 to as much as $0.50 a kilowatt-hour.

Environmental aspects

Offshore environmental impacts for marine energy technologies tend to be minimal. Few produce pollution while in operation. One exception is tidal barrages, where the creation of a large human-made seawater lake behind the barrage has the potential to affect fish and bird breeding and feeding, siltation, and so on. Another exception is OTEC, which may cause the release of carbon dioxide from seawater to the atmosphere.

The main issues, however, tend to be conflicts with other users of the seas - for fishing, marine traffic, and leisure activities. Of these, fishing is perhaps the main potential area of conflict. None of the technologies discussed seems likely to cause measurable harm to fish or marine mammals. But some - such as marine current turbines and wave power devices - may need small fishery exclusion zones to avoid entanglement with nets.

Implementation issues

Numerous legal hurdles await developers of offshore technologies in gaining licenses and permissions from the many marine agencies charged by governments with overseeing the environment, navigation, fisheries, and so on. Most of the marine renewable energy technologies are immature and not well developed, facing difficult engineering problems and higher-than-usual financial risks due to the high overheadsof running experimental systems at sea. If these technologies are to develop at a reasonable speed to make a significant contribution to clean energy generation, they will need much greater support for RD&D. In the end the power to make marine renewable energy technologies succeed (or fail) lies largely with governments.

Conclusion

- **Energy is in the seas in prodigious quantities. The question is whether it can be tapped, converted to a useful form, and delivered cost-effectively in comparison with other methods of energy generation. Several technologies show reasonable prospects for doing so.**

- **Tidal barrages have been tried in a limited way and abandoned as uneconomic, largely because they are very low-head hydro power plants with unusually high civil costs and an unusually poor load factor.**

- **Wave energy is beginning to see success with shoreline systems, but has yet to be effectively demonstrated on any scale near shore, let alone offshore, where most of the energy is found.**

- **Marine current energy is only just starting to be experimented with, but because it involves less technical risk than wave energy (conditions are less extreme), it promises to develop relatively quickly.**

- **OTEC, experimented with extensively, shows most promise as a multipurpose process (energy with cooling, nutrients for fish-farms, and/or potable water from seawater). Shoreline OTEC may possibly be more readily developed and economically applied than devices floating in deep waters.**

- **The two remaining known options - exploiting salinity gradients and cultivating marine biomass - seem a long way from any practical application.**

Wave energy remains
at an experimental stage,
with only a few prototype

systems actually working.

System aspects

Rapid changes in the energy sector, liberalisation of energy markets and the success of new technologies such as the combined cycle gas turbine offer challenges to the integration of renewable energy technologies into energy supply systems. They also lead to new issues at the system level.

System aspects come into play when there are many relatively small energy generation units, both renewable and conventional. The issues discussed here focus on electricity because of the instant response of electricity. Few thermal and fuel networks experience these issues because of their storage capacity.

With the rapid increase in the number of small generators connected to distribution networks at low and medium voltages, these networks need to handle more two-way flows of electricity, requiring decentralised intelligent control systems and local storage systems to increase reliability.

Trends in the energy sector

The energy sector is undergoing rapid change because of the following trends:

- **World-wide restructuring of utilities and liberalisation of energy markets.**
- **Greater choice for large and small customers.**
- **Customer interest in green pricing and the emerging trade in green certificates.**
- **Technological innovations in efficiency, demand-side management, transport and distribution, electronic power handling, and generation.**

These trends directly or indirectly affect the electricity system. Patterson (1999) describes how the global electricityindustry is in confusion, how long-accepted ground rules for technology, fuels, ownership, operation, management, and finance are changing by the day. The traditional shape of the electricity system is based on two pillars: large remote power stations generating centrally controller synchronised alternate current, and a monopoly franchise to finance, build, and operate the system.

Technical innovations, such as the gas turbine and advanced power electronics, are undermining the first pillar. Institutional innovation and price competition are undermining the second. In effect liberalisation and new technological development are democratising the system by decentralising it. And suddenly direct current, favoured by Edison, is discussed again, not least because it fits rather better into the micro-applications of computer chips and electronics (FT, 1998).

These trends are also summarised in the concept of the distributed utility, based on the principle that the economies of scale for large generation units are replaced by the economies of numbers in producing large quantities of small units: wind, photovoltaics, fuel cells, internal combustion engines, small gas turbines, and storage systems (Weinberg, 1995; Ianucci and others, 1999). The concept involves both energy efficiency and demand-side management measures at the customers' end, as well as distributed generation and distributed storage in the networks. For the customer it implies, in principle, lower energy prices, new and better services, and new products. Market studies in the United States indicate that in the traditional vertically integrated utility, distributed generation and storage could serve 20 - 40 percent of U.S. load growth. If the existing load could be served by distributed generation through replacement or retirement of central station generation, the potential is even greater (Ianucci and others, 1999).

Characteristics of renewable energy systems

From a system point of view, a distinction should be made between intermittent renewable energy sources (wind, solar photovoltaic) and those with a more stable and controllable output (hydro, biomass). The intermittent ones deliver primarily energy but only limited capacity, whereas the more stable ones deliver both. Note, however, that an intermittent resource can be transformed to baseload power supply if it is combined with an energy storage system.

Characterising the typical intermittent sources are capacity factors with values often a third or less of those of conventional systems. (The capacity factor is defined as the ratio of year-averaged system power to the rated system power.) In energy output per installed kilowatt, each year conventional power plants produce 4,000 - 7,000 kilowatt-hours per kilowatt of installed capacity, wind plants generally produce 2,000 - 2,500, and solar photovoltaic plants produce 750 - 1,500. The network should be designed to absorb that peak capacity and to provide electricity reliably when the intermittent sources are not available.

The renewable sources with an inherently stable output can, from a system point of view, be treated as conventional units: hydro and biomass-powered units, as well as OTEC and wave power. Hybrid solar thermal power stations co-fired with natural gas (or biofuels) are also regarded as conventional.

Electrical system design

Today's electrical system is designed for one-way traffic from the large generating unit through the transmission and distribution network to the customers. With the advent of smaller generating units distributed throughout the network, two-way traffic becomes more important and requires a rethinking of the network's design. New analytical tools are being developed for this purpose, and innovations in power electronics are becoming more important (Verhoeven, 1999). This is true for transmission lines where high voltage direct

current cables (equipped with power electronics at both ends) are preferred for bulk power transport. For medium-and low-voltage lines, power electronics are important in voltage conditioning, preventing voltage dips, and reactive power compensation. The electricity network should become more flexible, facilitating co-operation between generators, storage, and efficient energy consuming systems. In short, the intelligent network of the future will be able to 'talk' to its connected systems (Verhoeven, 1999).

> Most studies confirm that an intermittent renewable energy contribution up to 10-20 percent can easily be absorbed in electricity networks.

The effect of decentralised systems on the reliability of the network is of prime concern to the network operators. Studies by KEMA for the Dutch electricity system indicate that by introducing decentralised generators and storage systems (close to the customers) the reliability of the network can increase significantly. Where new grids are to be installed, the grid can become 'thinner' and built with less redundancy. And the transmission and distribution networks can become simpler because of intelligent control systems (Vaessen, 1997).

Model studies by the Pacific Northwest Laboratory confirm that distributed utility (DU) generation will have a significant impact on bulk transmission system stability at heavy penetration levels (Donelly and others, 1996). By locating DU technologies at points of critical loading, utilities may be able to defer upgrades of transmission and distribution facilities. Many utilities have already had operating experience with DU generation, and such local issues such as protection, interaction with distribution automation schemes, and reactive power control have been successfully resolved. Questions remain on how these resources, along with dispatchable generation and storage, interact with each other

as their penetration increases.

Grid integration of intermittent renewables

The amount of intermittent power that can be connected to a grid without problems of grid reliability or quality depends on many factors. Locally problems can occur quite soon when feeding substantial intermittent power (more than 100 kilowatts) into the low-voltage grid at one point. But it has been shown that penetration as high as 40 percent can be achieved for wind turbines (feeding into the medium-voltage grid). This is a subject for further investigation. Most studies confirm that an intermittent renewable energy contribution up to 10 - 20 percent can easily be absorbed in electricity networks. Higher penetration rates may require adequate control or such measures as output limiting or load shedding. Another approach could be to increase the flexibility of the electricity system by means of gas turbines. Penetration values up to 50 percent are possible for large systems with reservoir-based hydropower units (Grubb and Meyer, 1993; Kelly and Weinburg, 1993).

Intermittent renewables and energy storage

Large penetration of intermittent renewable energy technologies would become much easier with some cheap form of large-scale electricity storage, than the virtual storage. At present, however, any other form of electricity storage than the virtual storage offered by conventional plants to the grid seems unattractive.

In the Netherlands several studies in the 1980s analysed the possibilities of large pumped storage systems (storage capacity of 10 - 30 gigawatt-hours, discharge capacity of 1,500 - 2,000 megawatts-electric), both above ground and below ground, based on water or compressed air. Estimated investment costs ranged from $1,000 to $2,000 million (EZ, 1988). The studies were initiated partly because of the (then) estimated limited allowable penetration ratios for wind power into the grid. With the insight that higher penetration

ratios were possible, and because of the high investmentcosts, the immediate interest in storage evaporated.

Schainker provides estimates for the capital costs of electricity storage (Schainker, 1997; PCAST, 1999). Compressed air systems appear to be fairly attractive, both for 2-hour and 20-hour storage options (table 7.24). In Germany the Huntorf power plant near Bremen, commissioned in 1978, used compressed air as a storage medium for the compression part of the gas-turbine cycle. With cheap electricity, the air was stored in off-peak hours, to be used during peak hours as on input to the gas-turbine, co-fired with natural gas.

As noted, wind-generated electricity can be transformed from an intermittent resource to a baseload power supply if combined with compressed air energy storage (CAES), adding probably $0.01 a kilowatt-hour to the wind electricity production costs (Cavallo, 1995).

Value of renewables

For standalone systems, the value of renewables is often the value of the service. Examples are lighting, heating, cooling, cooking, pumping, transportation, and telecommunication. How this value should be evaluated is determined by the minimum cost of any equivalent alternative energy source or technology.

For grid-connected electricity systems, the value of renewables can be defined in different ways: avoided fuel, capacity, and maintenance costs; avoided electricity consumption costs; buy-back rate; and non-financial benefits (Turkenburg, 1992).

The avoided fuel costs in the conventional system usually represent the lowest possible value (typically $0.02 - 0.05 a kilowatt-hour). Renewables also have a capacity value, though this may be small for intermittent technologies (Alsema and others, 1983; van Wijk and others, 1992). For solar energy systems used for peak shaving (such as peaks due to air conditioning) or grid support, the value of photovoltaic power may be

substantially higher than the value of base-load power.

Avoided costs of electricity consumption refer to the situation where a renewable energy system is connected to the grid by a bidirectional kilowatt-hour meter. By definition, the value then becomes equal to the costs (tariffs) of normal electricity. In many countries this is in the range of $0.10 - 0.25 a kilowatt-hour for small users (IEA PVPS, 1997) In the buy-back rate method, the value of renewables can be lower or higher than that of energy from the grid. It is lower if an intermediate rate between avoided fuel costs and electricity tariffs is used, as is often the case (IEA PVPS, 1997).

It can be higher if a high value is given to the fact that it is green electricity. In some areas (parts of Germany) buy-back rates are based on true costs of renewables and may be as high as about $0.5 a kilowatt-hour for photovoltaics.

Finally, the value of renewables for the owners of a system may partly be non-financial, such as the mere fact that they cover (part of) their own consumption in an independent and clean way. Obviously this cannot be easily expressed in financial terms.

Conclusion

- **Current trends in the energy sector favour the emergence of distributed utilities, where growing numbers of relatively small renewable and conventional supply systems can be integrated, thanks to local intelligent control systems supported by local storage systems. When properly planned they can even improve the reliability of the networks, but continued research is required in such areas as network modelling.**

- **A fundamental change is taking place in the way electricity networks will be managed and used in the near future, thanks to the liberalisation of energy markets and the success of new technologies such as combined-cycle gas turbines and**

power electronics. The energy sector is moving away from the centralised massive supply of kilowatt-hours into supplying decentralised tailored services to its customers.

- **Penetration ratios of renewable energy systems realised without loss of supply security are around 10 - 20 percent or higher, depending on the characteristics of the total system. High penetration rates can be achieved with advanced power electronics, steadily improving weather prediction methods, availability of hydropower plants, and integration of storage systems.**

- **The value of energy carriers produced by renewable sources depends on local circumstances. In practice figures are $0.02 - 1.00 a kilowatt-hour.**

TABLE 7.24. OVERVIEW OF CAPITAL COSTS FOR ELECTRICITY STORAGE (1997 DOLLARS)

Technology	**Component capital cost**		**Total capital cost**	
	Discharge capacity (dollars per kilowatt)	**Storage capacity (dollars per kilowatt-hour)**	**2-hour storage (dollars per kilowatt)**	**20-hour storage (dollars per kilowatt)**
Compressed air				
Large (350 megawatts)	350	1	350	370
Small (50 megawatts)	450	2	450	490
Above ground (16 megawatts)	500	20	540	900
Conventional pumped hydro	900	10	920	1,100
Battery (target, 10				

megawatts)				
Lead acid	120	170	460	3,500
Advanced	120	100	320	2,100
Flywheel (target, 100 megawatts)	150	300	750	6,200
Superconducting magnetic storage (target, 100 megawatts)	120	300	720	6,100
Supercapacitors (target)	120	3,600	7,300	72,000

Source: PCAST, 1999.

Policies and instruments

New renewable energy technologies are trying to make a way into different markets, often in competition with other options to fulfil the demand for energy services. Contrary to assumptions in the 1970s and 1980s, shortages of oil and gas due to resource constraints are not expected in the nearest decades. And coal resources are very large. Increasing fossil fuel prices driven by resource constraints are not also expected in the nearest decades. So a transition to renew-ables-based energy systems must largely rely on:

- **Successful continuing development and diffusion of renewable energy technologies that become increasingly competitive through cost reductions from technological and organisational development.**

- **Political will to remove various barriers to the deployment of renewables and** internalise environmental costs and other externalities that permanently increase fossil fuel prices.

As many countries have demonstrated, a variety of incentive mechanisms can promote the development and use of renewable energy sources:

- The cost of competing conventional energy.
- Financing and fiscal policy.
- Regulation.
- Getting started new technologies.

Cost of competing conventional energy

Reduce subsidies. Subsidies for conventional energy are pervasive and reduce the competitiveness of renewables (chapter 12). They have often proved to be difficult to remove.

Internalise environmental costs. From a theoretical point of view, carbon dioxide taxes would be the simplest and most consistent method for internalising the costs of mitigating climate change. Similarly, taxes can be used to internalise other environmental costs associated with fossil fuels or external costs associated with nuclear power. Although the magnitude of the environmental cost for various energy supply alternatives is debated, they are relatively lower for renewable energy.

> The value of renewables for the owners of a system may partly be non financial, as they cover (part of) their own consumption in an independent and clean way.

Markets in many cases adapt quite rapidly to substantial changes in relative prices. Swedish carbon taxes are a case in point. The new energy and carbon taxes introduced in the early 1990s made bio-energy the least expensive fuel for heat production. Boilers are relatively flexible regarding fuel choice, and the market share of bio-energy in district heat production in Sweden increased from 9 percent (3.6 terawatt-hours) in 1990 to 30 percent (13.7 terawatt-hours) in 1998.

In general, however, this approach has not been particularly successful. Politically, it is difficult to gain acceptance for the large rise in energy prices that this approach could entail. At the national policy level, an important objection is the negative effect on the competitive position of domestic industries. A system of tradable emission permits or high taxes on marginal carbon dioxide emissions might circumvent this problem.

Financing and fiscal policy

Subsidies. Subsidies to stimulate the market penetration of renewables may be seen as the second-best solution to taxes - that is, relative prices are manipulated by subsidising what is desirable rather than taxing what is undesirable. Subsidies can take different shapes: investment subsidies (which give little incentive to actually produce), production subsidies (which may be perceived as unreliable and subject to change), and various indirect subsidies through preferential tax treatment, depreciation rules, and the like (see below). System benefit charges, such as the fossil fuel levy, are increasingly popular mechanisms to finance a subsidy for renewable energy through shifting the economic burden from taxpayers to consumers.

Financing. Financing arrangements are particularly important to renewable energy projects, which are often capital intensive, with many factors making their financing more expensive than for more traditional power investment (Wiser and Pickle, 1997). These

factors include real and perceived project risks, the small size of renewable energy industry and many renewable energy projects, and dependence on unpredictable government policies to promote renewable energy.

The right choice of financing schemes (private, corporate, participation, project, and third party), ownership (single, corporate, participation, project finance, and third party) and legal entities (personal, partnership, corporation, and co-operation) can have a decisive impact on the economic viability of a project (Langniss, 1999). In developing countries, financing adapted to local needs and tradition - such as through revolving funds - has proven important in the diffusion of small renewable energy technologies, such as household photovoltaic systems (Gregory and others, 1997). Coping with the demand put on financing by the specific characteristics of renewables is an important challenge for international and other financial institutions.

Taxation. As noted, general and specific tax rules can work for or against renewable energy. Preferential tax treatment, tax exemption, accelerated depreciation, and other approaches can promote renewable energy. The Netherlands, for example, is moving away from using direct subsidies to supporting renewables through a variety of tax incentives. As for other policies and measures, tax mechanisms must be carefully designed to avoid undesirable consequences such as low incentives for project performance, as in the California wind rush, which also disrupted the Danish wind industrywhen tax incentives where removed (Wiser and Pickle, 1997). Experiences were similar in the initial years of wind power development in India (Mathews, 1998a, b).

Market approaches. Increasing consumer willingness to pay a premium for renewable energy can generate the higher revenues that may be needed to recover production costs. This approach is spreading fast through the increased marketing of environmental labelling and green pricing, notably in North America and Europe. Retail competition and the subsequent need for suppliers to diversify and become more customer oriented is an

important driving force, an outcome of the commercial impulse to diversify and add value to basic products. Labelling can be done by a credible independent third party, such as an non-governmental organisation or government agency. In some cases electricity suppliers offer production-specified electricity, such as guaranteed annual average deliveries of wind electricity. The willingness to pay of large electricity users is likely to be low or nil, and green pricing may result only in modest additions of renewable energy. It can, however, nurse a market for new renewable technologies.

Regulation

The focus of most regulatory approaches to promote renewables has been the electricity sector. Regulation has also been used to introduce alternative transportation fuels, notably blending in ethanol with gasoline. Mechanisms to promote renewables through regulatory approaches can be categorised as obligations to buy and obligations to supply. Regulation in other domains can also have an influence.

Obligations to buy. Obligations to buy generally stipulate under what rules independent power producers get access to the grid and economic compensation for delivered electricity. This approach is commonly used in monopoly markets to ensure access for independent power producers with renewable energy. Regulated access and prices reduce transaction costs. Prices are usually based on avoided costs to the utility, and the principles by which these are calculated are important for the outcome. Obligations to buy may be complicated to maintain in liberalised electricity markets with competition between suppliers. The obligation to buy under the U.K. Non Fossil Fuel Obligation has been complemented with a mechanism for reimbursing electricity companies for the extra cost incurred.

Obligations to supply. Renewable portfolio standards can be used as an alternative to, or in combination with, system benefit charges to promote renewable electricity. A

renewable portfolio standard imposes an obligation on all electricity suppliers to include a stipulated fraction of renewable electricity in their supply mix. This obligation is sometimes combined with a system for renewable energy credits to facilitate trade of renewable electricity between suppliers. Renewable portfolio standards are being implemented or discussed in Europe and in several states in the United States. Voluntary or negotiated agreements are sometimes used as an alternative to regulation.

Regulation in other domains. Regulation and policies in other sectors or domains (agricultural policy, land-use planning), or the lack thereof, often inflict serious constraints or barriers to the use of renewable energy. For bio-energy, the prospects generally depend heavily on forestry and agricultural policy. In temperate regions a prime option for bio-energy is short rotation forests on agricultural land. But establishing an energy plantation means committing the land to one use for many years or even decades. In contrast, agricultural subsidies tend to change frequently, deterring most farmers from making this commitment.

A lack of regulation can also hinder exploitation. For example, the exploration and exploitation of such natural resources as minerals or fossil fuels are usually regulated through legislation and involve selling or giving concessions. The absence of corresponding regulation for wind concessions, which would secure the rights to a resource, can be a barrier to commercial investments in exploration and exploitation (Brennand, 1996). Consequently, coherence should be sought between regulation in the renewable energy area and in other domains.

Getting new technologies started

Widespread diffusion of new renewable energy technology also depends on a successful chain of research, development, deployment, and cost reduction before a technology is commercially viable. Once that stage is reached, success also depends on availability of

information about the resources, technologies, and institutional, organisational, and technical capabilities to adopt a technology to local conditions. This complex process, called the energy technology innovation pipeline, includes research, development, demonstration, buying down the cost of innovative energy technologies along their learning curves, widespread deployment, and involving of a range of actors (PCAST, 1999).

Research and development spending and priorities. In many areas, including the energy sector, the private sector under-invests in RR&D relative to the public benefits that could be realised from such investments, motivating public support for energy R&D. There are several examples of how electricity and gas sector restructuring is resulting in cutbacks on energy R&D and a shift to projects with short-term commercial benefits (PCAST, 1999). Government spending on energy R&D is collected and reported by the International Energy Agency for OECD countries (IEA, 1998). Between 1986 and 1996 the total reported annual energy R&D spending decreased by 19 percent, from about $11.0 billion to about $9.0 billion (1996 prices). But in the same period spending on energy conservation R&D increased by 64 percent to about $1.0 billion (1996 dollars) while spending on renewables R&D increased marginally from $700 million in 1986 to $720 million in 1996.

Demonstration and cost-reduction strategies. Demonstrations are necessary to test new energy-technology manufacturing (such as solar photovoltaics or fuel cells) and energy conversion facilities (such as integrated biomass gasification combined cycle plant) - and to prove their technical and economic viability. The private sector may find it difficult to build demonstration plants for various reasons - high capital requirements, required rates of return, high risk, and difficulties to appropriate the long-term benefits. Thus, public support is needed when clear public benefits can be associated with the technology.

In recent years, more attention has been going to the phase between demonstrations and commercial competitiveness. For essentially all technologies and production processes, a

substantial amount of experience or learning results from their application, which in turn reduces costs. For various products and processes a 0 - 30 percent reduction in costs has been observed with each doubling of cumulative production (Neij, 1999). This phenomenon - called the experience curve or learning curve - has motivated private firms to use forward pricing. That is, they initially sell products below production cost under the expectation that learning effects will drive down costs and that profits will be generated later. But for renewable energy, it may be difficult for an individual firm to recover the costs of forward pricing. Here public financial support in combination with other measures can be key to success. In the wind industry in Denmark, a combination of subsidies, physical planning, wind turbine certification, and the like has produced in a thriving industry with a 50 percent share of the world market (see chapter 12).

> Increasing consumers' willingness to pay a premium for renewable energy can generate the higher revenues that may be needed to recover production costs.

Building capacity for widespread deployment. Although a technology may be competitive, its widespread deployment also depends on a range of other factors. A new technology may face a range of barriers to its widespread application. These include high perceived risk, high transaction and information costs, uncertainty about resource availability, and low technical and institutional capabilities to handle this new technology. Taxes, financing, fiscal policy, legislation, and regulation are important to address such barriers and have been discussed above.

TABLE 7.25. CURRENT STATUS OF RENEWABLE ENERGY TECHNOLOGIES

Technology	Increase in installed capacity in past five years (percent a year)	Operating capacity, end 1998	Capacity factor (percent)	Energy production 1998	Turnkey investment costs (U.S. dollars per kilowatt)	Current energy cost of new systems	Potential future energy cost
Biomass energy							
Electricity	≈ 3	40 GWe	25 - 80	160 TWh (e)	900 - 3,000	5 - 15 ¢/kWh	4 - 10 ¢/kWh
Heat[a]	≈ 3	> 200 GWth	25 - 80	> 700 TWh (th)	250 - 750	1 - 5 ¢/kWh	1 - 5 ¢/kWh
Ethanol	≈ 3	18 bln litres		420 PJ		8 - 25 $/GJ	6 - 10 $/GJ
Wind electricity	≈ 30	10 GWe	20 - 30	18 TWh (e)	1,100 - 1,700	5 - 13 ¢/kWh	3 - 10 ¢/kWh
Solar photovoltaic electricity	≈ 30	500 MWe	8 - 20	0.5 TWh (e)	5,000 - 10,000	25 - 125 ¢/kWh	5 or 6 - 25 ¢/kWh
Solar thermal electricity	≈ 5	400 MWe	20 - 35	1 TWh (e)	3,000 - 4,000	12 - 18 ¢/kWh	4 - 10 ¢/kWh
Low-temperature solar heat	≈ 8	18 GWth (30 mln m^2)	8 - 20	14 TWh (th)	500 - 1,700	3 - 20 ¢/kWh	2 or 3 - 10 ¢/kWh
Hydroelectricity							
Large	≈ 2	640 GWe	35 - 60	2,510 TWh	1,000 -	2-8	2-8

				(e)	3,500	¢/kWh	¢/kWh
Small	≈ 3	23 GWe	20 - 70	90 TWh (e)	1,200 - 3,000	4 - 10 ¢/kWh	3 - 10 ¢/kWh
Geothermal energy							
Electricity	≈ 4	8 GWe	45 - 90	46 TWh (e)	800 - 3,000	2 - 10 ¢/kWh	1 or 2 - 8 ¢/kWh
Heat	≈ 6	11 GWth	20 - 70	40 TWh (th)	200 - 2,000	0.5 - 5 ¢/kWh	0.5 - 5 ¢/kWh
Marine energy							
Tidal	0	300 MWe	20 - 30	0.6 TWh (e)	1,700 - 2,500	8 - 15 ¢/kWh	8 - 15 ¢/kWh
Wave	-	exp. phase	20 - 35	-	1,500 - 3,000	8 - 20 ¢/kWh	-
Current	-	exp. phase	25 - 35	-	2,000 - 3,000	8 - 15 ¢/kWh	5 - 7 ¢/kWh
OTEC	-	exp. phase	70 - 80	-	-	-	-

a. Heat embodied in steam (or hot water in district heating), often produced by combined heat and power systems using forest residues, black liquor, or bagasse.

Information and transaction costs can be the target of specific government initiatives. For example, responsibility for mapping natural resources should lie with the government. Transaction costs can be reduced by simplified permitting procedures, physical planning, use of standardised contracts, and clear regulation for suppliers of electricity and fuels from renewables. Information costs for new technologies and risk may be effectively reduced through a government testing and certification procedure. Governments, as key

sponsors of the educational system in most countries, also have an obligation and an opportunity to support education and continuing education for practitioners.

Conclusion

Renewable energy sources supply 56 ± 10 exajoules a year (12 - 16 percent) of total world energy consumption (400 ± 10 exajoules in 1998). The supply is dominated by traditional biomass (probably 38 ± 10 exajoules a year), mostly firewood used for cooking and heating, especially in developing countries in Africa, Asia, and Latin America. A major contribution is made by large hydropower (about 9 exajoules a year). Another major contribution, estimated at 7 exajoules a year, comes from primary biomass used in modern energy conversion processes. The contribution from all other renew-ables (small hydropower, geothermal, wind, solar, and marineenergy) is about 2 exajoules a year.

Of the total biomass energy supply, 16 ± 6 exajoules a year is estimated to be commercial. The total primary energy supply from renewable sources in 1998 used commercially can be estimated at 27 ±6 exajoules. It is estimated that in 1998 new renewable energy sources - modern bio-energy, small hydropower, geothermal energy, wind energy, solar energy and marine energy - supplied 9 exajoules (about 2 percent).

The enormous potential of renewable energy sources can meet many times the world energy demand. They can enhance diversity in energy supply markets, contribute to long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services, particularly in developing countries and rural areas, create new employment opportunities, and offer opportunities to manufacture much of the equipment locally (IEA, 1997). A brief overview of the many technologies to exploit them is presented in table 7.25.

A number of factors will have to be overcome to increase the market deployment of

renewable energy technologies (IEA, 1997). Many technologies are still at an early stage of development. Their technological maturity will demand continuing research, development, and demonstration. Few renewable energy technologies can compete with conventional fuels on a strict cost basis, except in some niche markets in industrialised countries and in non-grid applications in developing countries. Clearly, the cost of production has to come down. As this chapter shows, substantial cost reductions can be achieved for most technologies, closing gaps and making renewables increasingly competitive (see table 7.25). This requires further technology development and market deployments and an increase in production capacities to mass-production levels.

Scenario studies investigating the potential contribution of renewables to global energy supplies indicate that this contribution might range from nearly 20 percent to more than 50 percent in the second half of the 21st century. We conclude that it is unclear what role renewables will play. Much will depend on the development of fossil-fuel energy supplies and the regulatory environment, especially for greenhouse gases (Eliasson, 1998). Contrary to assumptions in the 1970s and 1980s, shortages of oil and gas due to resource constraints are not expected in the nearest decades, and coal resources are very large. Therefore, apart from production and distribution constraints, substantially increasing fossil fuel prices driven by resource constraints are not expected in the nearest decades. In addition, advanced technology developments might allow fossil fuel use with greatly reduced atmospheric emissions (see chapter 8).

A transition to renewables-based energy systems would have to rely largely on successful development and diffusion of renewable energy technologies that become increasingly competitive through cost reductions resulting from technological and organisational development - and on the political will to internalise environmental costs and other externalities that permanently increase fossil fuel prices. Different technologies vary widely in their technological maturity, commercial status, integration aspects, and so on. Policies aimed at accelerating renewable energy must be sensitive to these differences. As

renewable energy activities grow and ever more extensive funding is required, many countries are moving away from methods that let taxpayers carry the burden of promoting renew-ables, towards economic and regulatory methods that let energy consumers carry the burden.

Notes

1. The capacity of a photovoltaic cell, module, or system is defined as the generating capacity at an irradiance of 1,000 watts a square metre (spectrum AM 1.5) and a cell temperature of 25 degrees Celsius.

2. This figure is obtained by comparing the 1989 installed potential of the 70 developing countries (185 gigawatts) from Moore and Smith (1990) and the value for 1997 (225 gigawatts) obtained from table 7.18.

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Chapter 8. Advanced Energy Supply Technologies

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ABSTRACT

Fossil energy technologies. Sustainability principles indicate that fossil energy technologies should evolve towards the long-term goal of near-zero air pollutant and greenhouse gas emissions - without complicated end-of-pipe control technologies. Near-term technologies and strategies should support this long-term goal.

The technological revolution under way in power generation - where advanced systems are replacing steam turbine technologies - supports this long-term goal. Natural-gas-fired combined cycles offering low costs, high efficiency, and low environmental impacts are being chosen wherever natural gas is readily available. Cogeneration is more cost-effective and can play a much larger role in the energy economy if based on gas turbines and combined cycles rather than on steam turbines.

Reciprocating engines and emerging microturbine and fuel cell technologies are strong candidates for cogeneration at smaller scales. Coal gasification by partial oxidation with oxygen to make syngas (mainly carbon monoxide, CO, and hydrogen, H_2) makes it possible to provide electricity through integrated gasifier combined cycle plants with air pollutant emissions nearly as low as for those plants using natural gas combined cycles. Today power from integrated gasifier combined cycle cogeneration plants can often compete with power from coal steam-electric plants in either cogeneration or power-only configurations.

Although synthetic liquid fuels made in single-product facilities are not competitive, superclean syngas-derived synthetic fuels that are produced in polygeneration facilities making several products simultaneously may soon be. Syngas can be produced from natural gas by steam reforming or other means or from coal by gasification with oxygen. Expanding markets for clean synthetic fuels are likely to result from toughening air pollution regulations. Synthetic fuels produced through polygeneration will be based on natural gas, if it is readily available. In natural-gas-poor, coal-rich regions, polygeneration based on coal gasification is promising.

The barriers to widespread deployment of advanced cogen-eration and polygeneration systems are mainly institutional. Most such systems will produce far more electricity than can be consumed on site, so achieving favourable economics depends on being able to sell coproduct electricity at competitive prices into electric grids. Utility policies have often made doing so difficult, but under the competitive market conditions towards which electric systems are evolving in many regions, cogeneration and polygeneration systems will often fare well.

Near-term pursuit of a syngas-based strategy could pave the way for widespread use of H_2 as an energy carrier, because for decades the cheapest way to make H_2 will be from fossil-fuel-derived syngas. Syngas-based power and H_2 production strategies facilitate the separation and storage of carbon dioxide from fossil energy systems, making it possible to obtain useful energy with near-zero emissions of greenhouse gases, without large increases in energy costs. Successful development of fuel cells would, in turn, facilitate introduction of H_2 for energy. Fuel cells are getting intense attention, because they offer high efficiency and near-zero air pollutant emissions. Automakers are racing to develop fuel cell cars, with market entry targeted for 2004 - 10.

Other advanced technologies not based on syngas offer some benefits relative to conventional technologies. But unlike syngas-based technologies, such options pursued in the near term would not offer clear paths to the long-term goal of near-zero emissions without significant increases in costs for energy services.

Nuclear energy technologies. World-wide, nuclear energy accounts for 6 percent of energy and 16 percent of electricity. Although it dominates electricity generation in some countries, its initial promise has not been realised. Most analysts project that nuclear energy’s contribution to global energy will not grow and might decline in the near future. Nuclear power is more costly than originally expected, competition from alternative technologies is increasing, and there has been a loss of public confidence because of

concerns relating to safety, radioactive waste management, and potential nuclear weapons proliferation.

Because nuclear power can provide energy without emitting conventional air pollutants and greenhouse gases, however, it is worth exploring whether advanced technologies might offer lower costs, restore public confidence in the safety of reactors, assure that nuclear programmes are not used for military purposes, and facilitate effective waste management.

In contrast to Chernobyl-type reactors, the light water reactors (LWRs) that dominate nuclear power globally have had a good safety record, though this has been achieved at considerable cost to minimise the risk of accidents.

The potential linkage between peaceful and military uses of nuclear energy was recognised at the dawn of the nuclear age. Steps taken to create a non-proliferation regime through treaties, controls on nuclear commerce, and safeguards on nuclear materials have kept peaceful and military uses separate. But if there is to be a major expansion of nuclear power, stronger institutional and technological measures will be needed to maintain this separation both for proliferation by nations and theft of weapons-usable materials by subnational groups.

Reactor vendors now offer several evolutionary LWRs with improved safety features and standardised designs, and there is some ongoing work on new reactor concepts.

Limited supplies of low-cost uranium might constrain LWR-based nuclear power development after 2050. Plutonium breeder reactors could address the resource constraint, but keeping peaceful and military uses of nuclear materials separate would be more challenging with breeders. Other possibilities for dealing with the resource constraint are extraction of uranium from seawater and thermonuclear fusion. There are many uncertainties regarding such advanced technologies, and all would take decades to

develop.

Radioactive waste by-products of nuclear energy must be isolated so that they can never return to the human environment in harmful concentrations. Many in the technical community are confident that this objective can be met. But in most countries there is no consensus on waste disposal strategies. The current stalemate regarding waste disposal clouds prospects for nuclear expansion.

The arguments for marginal, incremental change are not convincing - not in this day and age. The future, after all, is not linear. History is full of sparks that set the status quo ablaze.

- Peter Bijur, chief executive officer and chairman, Texaco, keynote speech to 17th Congress of World Energy Council, Houston, 14 September 1998

This chapter discusses advanced energy supply technologies with regard to their potential for facilitating the widespread use of fossil and nuclear energy sources in ways consistent with sustainable development objectives.[1] In each case the current situation is described, goals for innovation are formulated in the context of these objectives, near-term and long-term technology options are discussed in relation to these goals, and illustrative cost estimates are presented for options with reasonably well-understood costs.*

> *** Life-cycle costs are presented for an assumed 10 percent real (inflation-corrected) cost of capital (discount rate), neglecting corporate income and property taxes. Neglecting such taxes is appropriate in a global study such as this report, partly because tax codes vary markedly from country to country, and partly because such taxes are transfer payments rather than true costs. Moreover, such capital-related taxes discriminate against many capital-intensive technologies that offer promise in addressing sustainable development objectives. Including such**

taxes, annual capital charge rates - including a 0.5 percent a year insurance charge - are typically 15 percent for a plant with a 25-year operating life, in comparison with 11.5 percent when such taxes are neglected (U.S. conditions).

Advanced fossil energy technologies

Fossil fuel supply considerations as a context for fossil energy innovation

Fossil energy technology development will be strongly shaped by energy supply security concerns and environmental challenges.

The emerging need for oil supplements in liquid fuel markets

Oil, the dominant fossil fuel, accounted for 44 percent of fossil fuel use in 1998. Although there is no imminent danger of running out of oil (chapter 5), dependence on oil from the Persian Gulf, where remaining low-cost oil resources are concentrated, is expected to grow. For example, the U.S. Energy Information Administration projects in its reference scenario that from 1997 - 2020, as global oil production increases by nearly 50 percent, the Persian Gulf's production share will increase from 27 to 37 percent (EIA, 1999a). This increase suggests the need to seek greater supply diversity in liquid fuel markets to reduce energy supply security concerns (chapter 4).

In addition, growing concerns about air quality are leading to increased interest in new fuels that have a higher degree of inherent cleanliness than traditional liquid fuels derived from crude oil, especially for transportation applications. To meet growing fluid fuel demand in the face of such constraints, some combination of a shift to natural gas and the introduction of clean synthetic fuels derived from various feedstocks (natural gas, petroleum residuals, coal, biomass) is likely to be needed to supplement oil during the next 25 years.

The oil crises of the 1970s catalysed major development efforts for synthetic fuels. For example, U.S. President Jimmy Carter's administration supported a synfuels programme that involved large government-supported commercialisation projects. Most such projects failed because the technologies were rendered uneconomic by the collapse of world oil prices in the mid-1980s. But, as will be shown, emerging synfuel technologies generally have better environmental characteristics and, when deployed through innovative multiple-energy-product (poly-generation) strategies, reasonably good economic prospects, even at relatively low oil price levels. Moreover, the private sector, rather than the government, is taking the lead in advancing these new technologies. The government's role has shifted from managing demonstration projects to supporting research and development that enables private-sector-led commercialisation and to helping remove institutional barriers to deployment.

Entering the age of gas

For natural gas, the cleanest, least-carbon-intensive fossil fuel, ultimately recoverable conventional resources are at least as abundant as for oil (chapter 5). Although the global consumption rate for gas is about half that for oil, the abundance of natural gas and its economic and environmental attractiveness have led it to play a growing role.[2] Since 1980 the share of natural gas in the global energy economy has grown, while oil and coal shares have declined. Wherever natural gas supplies are readily available, the natural-gas-fired gas-turbine - steam-turbine combined cycle (NGCC) has become the technology of choice for power generation, in which applications it is typically both the cleanest and least-costly fossil fuel option. As will be shown, clean natural-gas-derived synthetic fuels also have good prospects of beginning to compete in liquid fuels markets.

For developing countries, the huge investments needed for natural gas infrastructure (pipelines, liquid natural gas facilities) are daunting. But NGCC plants might be built as targeted initial gas users, using the revenues to facilitate infrastructure financing.

Alternatives to conventional gas might be needed to meet the growing demand for fluid fuels in 2025 - 50. Options include synthetic fluid fuels derived from coal and various unconventional natural gas resources (chapter 5).

Unconventional natural gas resources associated with methane hydrates are especially large, although the quantities that might be recoverable and delivered to major markets at competitive costs are highly uncertain (chapter 5). There is little private sector interest in better understanding the magnitude and cost dimensions of the methane hydrate resource, because conventional natural gas supplies are abundant on time scales of interest to business.

An understanding of methane hydrate issues is important for decisions on near-term research and development priorities related to unconventional gas resource development versus coal synthetic fuels development. For this reason - as well as the theoretical potential of the hydrate resource and the attractions of natural gas as an energy carrier - the U.S. President's Committee of Advisors on Science and Technology has urged international collaborative research and development in this area, building on embryonic efforts in India, Japan, and Russia (PCAST Energy Research and Development Panel, 1997; PCAST Panel on ICERD[3], 1999).

The drawbacks and attractions of coal

Coal use is declining in most industrialised countries other than the United States, where use is expected to grow slowly. World-wide, coal use is expected to grow as fast as oil use, with much of the growth accounted for by China, whose global share might increase from 30 percent today to nearly 50 percent by 2020 (EIA, 1999a).

For coal, the dirtiest, most carbon-intensive fossil fuel, global resources are abundant (chapter 5). Coal is generally less costly than other fossil fuels. Substantial productivity

gains have been made for coal production in both Australia and the United States (Williams, 1999b). Such gains can be expected in other regions once energy market reforms are put in place. Productivity gains have caused coal prices in the United States to decline by a factorof 2 since the early 1980s, to a level half that for natural gas.

During the next 20 years, a 20 percent rise in the price of natural gas and a 30 percent drop in the price of coal are expected in the United States (EIA, 1998a), leading to growth in the price ratio to 3.5. In Europe coal prices are not as low as in the United States, but even there the average price of coal imported into the European Union fell by more than a factor of 2 between 1983 and 1995 (Decker, 1999).

Although many regions are moving away from coal, this chapter shows that there are reasonable prospects that improved technology could propel a shift back to coal by making it feasible to provide from coal, at attractive costs, energy systems characterised by near-zero emissions of both air pollutants and greenhouse gases. Concerted efforts to develop and commercialise such technologies are desirable in light of the strategic importance of coal to coal-rich countries where conventional oil and natural gas resources are scarce (for example, China and India).

Setting goals for advanced fossil energy technologies

Designing advanced fossil energy technologies to be compatible with sustainable development requires that:

- **Fossil energy be widely affordable.**
- **Fossil energy help satisfy development needs not now being met.**
- **Energy supply insecurity concerns be minimised.**
- **Adverse environmental impacts be acceptably low.**
- **For the longer term, emissions of carbon dioxide (CO_2) and other greenhouse**

gases be sufficiently low to meet the objectives of the United Nations Framework Convention on Climate Change (UNFCC, 1992).[3]

The most formidable challenges facing the fossil energy system are likely to be achieving near-zero emissions of air pollutant and CO_2 emissions.

If fossil fuels are to play major roles in. facilitating sustainable development, all these objectives must be met simultaneously - which is impossible with today's technologies. Thus there is a need for substantial research, development, demonstration, and deployment programmes aimed at launching advanced, sustainable fossil energy technologies in the market. Because resources available to support energy innovation are scarce (and the fossil energy community must share these scarce resources with the end-use energy efficiency, renewable energy, and nuclear energy communities), criteria should be established for the long-term goals of the innovation effort. In addition, alternative technological strategies should be assessed with regard to their prospects for meeting these goals. This section introduces sustainable development goals for advanced fossil energy technologies. Later sections discuss the prospects for meeting these goals with alternative clusters of technologies.

The objective of making energy widely affordable is satisfied for most consuming groups with existing fossil energy technologies, which tend to be the least costly energy supplies. Addressing other sustainability objectives simultaneously will tend to increase costs. However, advanced technologies can help contain costs when these other objectives are also pursued. Moreover, as will be shown, new approaches to organising energy systems

so that multiple products are made in a single facility - polygeneration strategies - can also lead to lower energy costs. The fossil energy technologies with the greatest potential to meet environmental goals are especially well-suited to polygeneration.

A key aspect of the objective of satisfying unmet energy needs for development involves giving the poor - especially the rural poor in developing countries - access to clean, modern energy carriers. Clean cooking fuels and electricity to satisfy basic needs are particularly important (chapters 2, 3, and 10). Advanced fossil energy technologies can help address these needs. Innovations in synthetic fuel technology, together with the attractive economics associated with deploying such technologies in polygeneration configurations, make the prospects for clean synthetic fuels much brighter today than they have been.

Some of the most promising synthetic fuels (such as dimethyl ether, or DME) are attractive energy carriers for serving both cooking fuel and transportation markets. The revolution in power-generating technology and the market reforms that are making small-scale power generation (reciprocating engines, microturbines, fuel cells) increasingly attractive economically in grid-connected power markets can also be deployed in remote rural markets, many of which are not currently served by grid electricity. Even in such markets where fossil fuels are not readily available, these systems can be adapted for use with locally available biomass resources in rural areas (Mukunda, Dasappa, and Srinivasa, 1993; Kartha, Kruetz, and Williams, 1997; Henderick, 1999; Henderick and Williams, 2000). Likewise, clean synthetic fuels for cooking can also be derived from biomass (Larson and Jin, 1999). Fossil energy technology advances have made biomass applications feasible for both small-scale power generation and synthetic cooking fuel production.

To a large extent, the objective of minimising energy supply insecurity concerns can be addressed with advanced fossil energy technologies by pursuing opportunities to diversify

the supply base for fluid fuels. Especially promising are opportunities to make synthetic fluid fuels through polygeneration strategies - using petroleum residuals, natural gas, and coal as feedstocks as appropriate, depending on local resource endowments. And for the longer term, successful development of methane clathrate hydrate technology could lead to improved energy security for a number of economies that heavily depend on imported hydrocarbons but have large off-shore hydrate deposits (such as India, Japan, Republic of Korea, and Taiwan, China).

The objective of making adverse environmental impacts acceptably low requires addressing the question: how low is low enough? Among environmental impacts, air pollution effects are especially important, for developing and industrialised countries alike. Moreover, adverse health impacts of air pollution tend to dominate overall air pollution impacts (chapter 3).

For many developing countries, the cost of the environmental damage caused by air pollution is high even though per capita energy consumption is low - mainly because pollution controls are largely lacking.[4] Costs from air pollution are also high for industrialised countries with strong pollution controls,[5] not only because of much higher energy consumption but also because the cost of uncontrolled emissions grows much faster than energy consumption, given that economists measure these costs on the basis of willingness to pay to avoid these damages (chapter 3).[6] Tables 8.1 and 8.2 show that even low estimates of these damage costs are significant relative to typical direct economic costs (direct costs are $0.03 - 0.04 a kilowatt-hour for electricity and $0.20 - 0.30 a litre for transport fuels) for both coal power plants and for automobiles, but are low for modern natural gas power plants.[7]

Here it is assumed that a major long-term goal for advanced fossil energy technology that is implicit in the objective of making adverse environmental impacts acceptably low is

near-zero air pollutant emissions - without the need for complicated and costly end-of-pipe control technologies. 'Near-zero emissions' is taken to mean emissions so low that residual environmental damage costs are a tiny fraction of the direct economic cost of energy. 'Long-term' is defined as 2015 and beyond. Thus the goal of near-zero emissions is a target for energy innovation (research, development, demonstration, early deployment) rather than a near-term regulatory goal. There are five readily identifiable reasons for setting such an ambitious goal for emissions.

TABLE 8.1. EMISSION RATES FOR AND ESTIMATED COSTS OF ENVIRONMENTAL DAMAGE FROM AIR POLLUTANT EMISSIONS OF FOSSIL FUEL POWER PLANT (LOW VALUATION FOR TYPICAL EUROPEAN CONDITIONS)

	Emission rate (grams per kilowatt-hour)			Low estimate of costs of environmental damages (dollars per thousand kilowatt-hours)[a]				Environmental damage costs relative to NGCC
Primary air pollutant	**SO_2**	**NO_x**	**PM_{10}**	**SO_2**	**NO_x**	**PM_{10}**	**Total**	**Total**
Average U.S. coal steam-electric plant, 1997	6.10[b]	3.47[b]	0.16[c]	15.9	13.9	0.7	30.5	82
New coal steam-electric plant with best available control technology[d]	0.46	0.87	0.15[c]	1.2	3.5	0.6	5.3	14
Coal IGCC plant[e]	0.075	0.082	0.0025	0.20	0.33	0.01	0.54	1.5
NGCC plant[f]	-	0.092	-	-	0.37	-	0.37	1.0

a. Environmental damage costs from power plant air pollutant emissions are assumed to be 25 percent of the median estimates of Rabl and Spadaro (2000) for typical power plant sitings in Europe. (The Rabl and Spadaro calculations were carried out under the European Commission's ExternE Programme. Nearly all the estimated costs of environmental damages are associated with adverse health impacts; the economic values of health impacts were estimated on the basis of the principle of willingness to pay to avoid adverse health effects.) Rabl and Spadaro considered a wide range of pollutants, but the only significant damage costs were from SO_2, NO_x, and PM_{10}, for which their median estimates of damage costs (in dollars per kilogram) were \$10.44, \$16.00, and \$17.00. Damage costs at 25 percent of the median estimates of Rabl and Spadaro (equivalent to one standard deviation belowthe median) are assumed, to put a conservatism into the calculation to reflect the scientific uncertainty. b. Average emission rates in 1997 for U.S. coal plants, whose average efficiency was 33 percent (EIA, 1998b). c. In 1990 PM_{10} emissions from U.S. electric utility coal power plants amountedto 245,000 tonnes (Spengler and Wilson, 1996) when these plants consumed 17.1 exajoules of coal (EIA, 1998b), so the PM_{10} emission rate was 14.34 grams per gigajoule - the assumed emission rate for all steam-electric cases in this table. d. It is assumed that the new coal steam-electric plant is 35.5 percent efficient; that the coal contains 454 grams of sulphur per gigajoule (1.08 percent sulphur by weight), the average for U.S. coal power plants in 1997 (EIA, 1998b); that SO_2 emissions are reduced 95 percent, a commercially feasible rate; and that the NO_x emission rate is 86 grams per gigajoule - achievable with advanced low-NO_x burners that will be commercially available shortly; e. It is assumed that the coal integrated gasifier combined cycle (IGCC) plant is 43.8 percent efficient, based on use of steam-cooled gas turbines (see table 8.4); that the emission rates equal the measured values for

the Buggenum coal IGCC plant (Netherlands): 10.0 and 0.3 grams per gigajoule of coal for NO_x and particulates, respectively, as well as 99 percent sulphur recovery (data presented by Co van Liere, KEMA, at the Gasification Technologies Conference in San Francisco, 17 - 20 October 1999); and that the coal contains 454 grams of sulphur per gigajoule. f. It is assumed that the natural gas combined cycle (NGCC) plant is 54.1 percent efficient, based on use of steam-cooled gas turbines (see table 8.4); and that the NO_x emission rate is 9 parts per million on a dry volume basis (at 15 percent O_2), corresponding to an emission rate of 0.092 grams per kilowatt-hour.

TABLE 8.2. EMISSION RATES FOR AND ESTIMATED COSTS OF ENVIRONMENTAL DAMAGE FROM AIR POLLUTANT EMISSIONS OF AUTOMOBILES (LOW VALUATION FOR TYPICAL FRENCH CONDITIONS)

Fuel and driving environment	Fuel economy (kilometres per litre)	Emission rate (grams per kilometre)		Low estimate of costs of environmental damages, EU conditions[a] (dollars)							
				Per kilogram		Per thousand kilometres of driving			Per thousand litres of fuel consumed		
		NO_x	PM	NO_x	PM	NO_x	PM	Total[b]	NO_x	PM	Total[b]
Gasoline[c]											
Urban[d]	8.7	0.68	0.017	5.5	690	3.7	11.7	16.6	32	102	144
Rural[d]	10.3	0.79	0.015	6.8	47	5.4	0.71	7.3	56	7.3	75
Diesel											

Diesel											
Urban^d	10.4	0.75	0.174	5.5	690	4.1	120	125	43	1250	1300
Rural^d	12.7	0.62	0.150	6.8	47	4.2	7.1	12.5	53	90	159

a. Environmental damage costs from automotive air pollutant emissions are assumed to be 25 percent of the median estimates presented in Spadaro and Rabl (1999) and Spadaro and others (1998) - calculations carried out under the European Commission's ExternE Programme. Nearly all the estimated costs of environmental damages are associated with adverse health impacts; the economic values of health impacts were estimated on the basis of the principle of willingness to pay to avoid adverse health effects. Damage costs at 25 percent of the mean estimates in these studies (equivalent to one standard deviation below the median) are assumed, to put a conservatism into the calculation to reflect the scientific uncertainty. b. Total costs per kilometre include, in addition to costs associated with NO_x and PM emissions, costs associated with emissions from CO, volatile organic compounds (VOC), SO_2, and benzo-a-pyrene (BaP). c. For a gasoline internal combustion engine car equipped with a catalytic converter. d. Urban cost estimates are for driving around Paris, where the average population density is 7,500 per square kilometre. Rural costs estimates are for a trip from Paris to Lyon, for which the average density of the population exposed to the automotive air pollution is 400 per square kilometre.

First, air pollution damage costs are associated largely with small-particle pollution, for which there appears to be no threshold below which the pollution is safe (chapter 3). Second, the trend has been towards continually more stringent controls on emissions in industrialised countries, both as a result of improved knowledge of adverse impacts and of increasing societal demands for cleaner air as incomes rise. But meeting air quality goals by continually ratcheting up the required end-of-pipe controls has proven very costly -

both because the cost of reducing emissions by the next increment tends to increase sharply with the level of reduction, and because the continual technological change required to keep up with evolving regulatory goals can be very costly when there is not enough time between changes in regulations to recover the cost of the last incremental improvement before the next one must be made.

Third, regulations calling for ever tighter end-of-pipe controls on emissions are sometimes not nearly as effective in meeting air quality goals as they are supposed to be, as is illustrated by the wide gap between actual emission levels and regulated emission levels for U.S. cars - a gap that has been projected to increase in the future, as regulations tighten (table 8.3).[8] Fourth, even for developing countries, the long-term near-zero emissions goal makes sense, because much of the energy technology that will be put into place in the period 2015 - 25 will still be operating decades later when incomes and societal desires for clean air will be high.[9] And fifth, there are promising technological options for converting the near zero emissions goal into reality. For example, managers of the U.S. Department of Energy's fossil energy programme have enough confidence in this idea to have created a new programme that seeks to develop new fossil energy technologies by 2015 that are characterised, among other things, by near-zero air pollutant emissions, as well as zero solid and liquid waste discharges.[10]

The challenge of setting goals with regard to the objective of preventing dangerous anthropogenic interference with the climate system is complicated by the fact that there is not yet agreement in the global community as to the level at which atmospheric CO_2 should be stabilised. However, the level that is eventually decided on is likely to be far below the level to which the world would evolve for an energy system that would follow a business-as-usual path. The IS92a scenario of the Intergovernmental Panel on Climate Change might be considered a business-as-usual energy future (IPCC, 1995). In this scenario the CO_2 emission rate grows from 7.5 gigatonnes of carbon (GtC) in 1990 (6.0

GtC from fossil fuel burning plus 1.5 GtC from deforestation) to 20 GtC in 2100. By way of contrast, stabilisation at twice the pre-industrial CO_2 level (550 parts per million by volume, a target favoured by various groups) would require reducing annual fossil energy emissions to 5.5 GtC by 2100. Stabilisation at 450 parts per million by volume (up from 360 parts per million by volume today) would require emissions falling to about 2.5 GtC by 2100 (DOE, 1999).

Many believe that coping adequately with the challenge of climate change will require major shifts to renewable energy sources, nuclear energy sources, or both. Although such shifts might be desirable for a variety of reasons, climate change concerns do not necessarily require a major shift away from fossil fuels. To be sure, the dimensions of the challenge are such that the deep reductions in CO_2 emissions that might be required during the next 100 years cannot be achieved only by making efficiency improvements in fossil energy conversion, however desirable energy efficiency improvements might be. But energy efficiency improvement is not the only option for reducing CO_2 emissions from fossil fuels. The energy content of these fuels can also be recovered while preventing the release of CO_2 into the atmosphere - for example, by separating out the CO_2 and sequestering it in geological formations or in the deep ocean.

There is growing optimism in the scientific and technological communities that fossil energy systems can be made compatible with a world of severely constrained greenhouse gas emissions (Socolow, 1997). This optimism is reflected in new fossil energy research and development programmes (for example, in Japan, Norway, and the United States) that aim to achieve near-zero emissions from fossil energy systems. As will be shown, even with some already developed technologies it appears feasible to achieve deep reductions in CO_2 emissions without large increases in fossil energy costs. Although uncertainties regarding storage security and potentially adverse environmental impacts (especially for ocean sequestration) must be resolved before a high degree of confidence can be assigned

to this option, there is growing scientific confidence that the potential for sequestering CO_2 is vast.

How can such considerations be used to frame goals for advanced fossil energy technologies that are consistent with the UN Framework Convention on Climate Change, when global society has not yet decided what goal is needed? In light of the long lead times required to bring new technologies to market at large scales, and considering that energy research and development is cheap insurance for addressing the climate change challenge (PCAST Energy Research and Development Panel, 1997), it is assumed here that a major element of the overall fossil energy innovation effort should be to develop the capacity to achieve deep reductions in CO_2 and other greenhouse gases. Thus, if global society eventually decides that deep reductions are needed, the fossil energy community will be prepared to respond with advanced technologies and strategies. As with air pollution, the goal of reducing greenhouse gas emissions to near zero is a target for capacity development through technological innovation over the long term, rather than for near-term regulations.

Of the challenges facing the fossil energy system in moving towards sustainable development, the most formidable are likely to be near-zero emissions of air pollutants and CO_2. Consequently, these two challenges are given the greatest emphasis in the following sections.

Technologies and strategies for moving towards near-zero emissions

This section describes fossil energy technologies and strategies that offer considerable promise to meet all the sustainable development criteria set forth in the previous section, including, for the longer term, the especially daunting criteria of near-zero emissions of both air pollutants and greenhouse gases. Near-zero emissions could be achieved in the long term if the dominant energy carriers were electricity and hydrogen (H_2). The

importance of having H_2 as an option complementing electricity as an energy carrier is discussed in box 8.1.

Here technologies are first discussed for power generation and then for synthetic fuels production. Key near-term strategies to hasten the widespread use of these technologies are cogeneration (combined heat and power) and polygeneration, which entails the simultaneous production of various combinations of synthetic fuels, electricity, process heat, and chemicals. Cogeneration and polygeneration offer favourable economics that can facilitate the industrial development of energy production technology based on synthesis gas (a mixture of gases consisting mainly of CO and H_2), which will subsequently be called syngas. Syngas is a key intermediate energy product that makes it possible to make many clean final energy products from fossil fuels - including, for the longer term, H_2.

TABLE 8.3. ESTIMATED COSTS OF ENVIRONMENTAL DAMAGE FROM NO_X EMISSIONS OF AUTOMOBILES (LOW VALUATION FOR TYPICAL FRENCH CONDITIONS, ASSUMING U.S. REGULATED AND ESTIMATED ACTUAL EMISSION LEVELS)

Model year	NO_x emission rate (grams per kilometre)		Estimated environmental damage cost (dollars per thousand kilometres, low estimate, French conditions; 55 percent urban + 45 percent rural driving, so that average cost = $6.1 per kilogram)[a]		New car fuel economy (kilometres per litre)	Estimated environmental damage costs (dollars per thousand litres of gasoline)	
	Regulated level	Estimated actual	Emissions at regulated level	Estimated actual emissions		Emissions at regulated	Estimated actual emissions

		level[b]				level	
1993	0.62	1.1	4	7	11.8	45	79
2000	0.25	0.8	2	5	11.9	18	58
2010	0.12	0.5	1	3	12.8	9	39

a. Low estimates of the costs of environmental damages for NO_x emissions from gasoline-powered automobiles operated under French conditions (from table 8.2): $5.5 per kilogram for urban areas and $6.8 per kilogram for rural areas. For regions other than France, costs at the same per capita GDP levels will scale roughly according to the regional population density. b. From Ross, Goodwin, and Watkins, 1995.

BOX 8.1. THE STRATEGIC IMPORTANCE OF HYDROGEN AS AN ENERGY CARRIER

For the long term, it is desirable that the energy system be based largely on inherently clean energy carriers. Like electricity, during its use hydrogen (H_2) generates zero or near-zero emissions of air pollutants and CO_2. And, as for electricity, it can be produced from fossil fuels as well as from non-carbon-based primary energy sources through various processes characterised by near-zero emissions of air pollutants and CO_2 (see the section below on enhancing prospects for H_2).

The importance of having H_2 as well as electricity as an inherently clean energy carrier stems from the difficulty of using electricity efficiently and cost-effectively in some important markets such as transportation. In principle, near-zero emissions could be realised throughout the energy economy with electricity, which accounts for a third of global CO_2 emissions from burning fossil fuels. In practice, however, for most applications electricity use is limited mainly to systems that can be supplied with electricity relatively continuously from stationary sources, because of the difficulties that have been encountered in evolving suitable cost-competitive electricity storage technologies.

Consider that although the zero-emissions mandate for cars in California was focused initially on developing battery-powered electric cars, the goal of producing light-weight, low-cost batteries with adequate range between rechargings has proven an elusive technological challenge; this difficulty is one of the factors that has resulted in refocusing much of the zero-emission-vehicle quest on fuel cells, with the expectation that ultimately fuel cell vehicles will be fuelled with H_2. Although storing H_2 onboard vehicles is more difficult than storing liquid fuels, providing enough low-cost storage capacity to reduce refuelling rates to acceptable levels for consumers is a far less daunting challenge for H_2 than for electricity.

More generally, development of near-zero-emitting H_2 energy systems is desirable because modellers expect, under business-as-usual conditions, major continuing high demand levels for fluid (liquid and gaseous) fuels and high levels of CO_2 emissions associated with fluid fuels production and use. Consider, for example, the reference IS92a scenario (IPCC, 1995). Although electricity's share of worldwide secondary energy consumption grows from 15 percent in 1990 to 28 percent in 2100, the fluid fuel share is only slightly less in 2100 than in 1990 (57 versus 64 percent) in the IS92a scenario.

Moreover, because of the projected rapidly growing importance of synthetic fuels after 2050, fluid fuel production accounts for 60 percent of IS92a's 20 GtC of total energy-related CO_2 emissions in 2100, up from 47 percent of the 6 GtC of total energy-related CO_2 emissions in 1990. Thus, even if electricity generation could be made 100 percent free of CO_2 emissions by 2100 (through a shift of projected fossil electric generation to some mix of renewable energy, nuclear energy, and decarbonised fossil energy), emissions in 2100 would still be double those of 1990 (even though CO_2-neutral biomass produced at a rate equivalent to more than half of total primary energy use in 1990 provides a third of total synthetic fuels in 2100).

Having available H_2 as well as electricity provided by production systems with near-zero emissions would provide society with the capacity to achieve, in the longer term, deep reductions in CO_2 emissions from the fluid fuel sectors as well as from the electric sector, and thereby help make it possible to limit the CO_2 level in the atmosphere to twice the pre-industrial level or less in response to climate change concerns.

Advanced technologies for power generation and cogeneration

Promising advanced power generation and cogeneration technologies for the near (less than 5 years) to medium (5 - 15 years) term include natural-gas-fired gas-turbine-based technologies, coal integrated gasifier combined cycle (IGCC) technologies, small engines suitable for distributed cogeneration applications, and various fuel cell technologies.

Natural-gas- and gas-turbine-based technologies. The pace of technological change has been brisk for gas turbines,[11] to the point where efficiencies are now comparable to those for coal steam-electric plants, even though turbine exhaust gas temperatures are high. To avoid wasting exhaust gas heat, gas turbines used in central-station power plants for purposes other than meeting peak loads are typically coupled through heat recovery steam generators to steam turbines in gas turbine - steam turbine combined cycles.

Table 8.4 presents cost and performance characteristics of two NGCC units: a 50 percent efficient* Frame 7F unit (commercially available) equipped with air-cooled gas turbine blades and a 54 percent efficient Frame 7H unit (available in 2000 or after) equipped with steam-cooled turbine blades.[12] In competitive power markets, installed costsof NGCCs have fallen to less than $500 per kilowatt-electric. For typical U.S. and European fuel prices, modern NGCCs can provide electricity at lower cost and about 60 percent less CO_2 emissions per kilowatt-hour than coal steam-electric plants (see table 8.4).

*** Efficiences in this chapter are expressed on a higher heating value (HHV) basis unless explicitly indicated otherwise.**

Thermal nitrogen oxide (NO_X) generated in the combustor by oxidising nitrogen from the air at high flame temperatures is the only significant air pollutant arising from NGCC operation. But even in areas with tight regulations on NO_X emissions,13 modern NGCCs are often able to meet regulatory requirements without having to install costly end-of-pipe controls, by premixing fuel and air for the combustor and thereby avoiding high flame temperatures. With this technology, NO_X emissions per kilowatt-hour are only 10 percent of those for coal steam-electric plants equipped with the best available control technology, and overall costs of pollution damages from NGCCs are one-fourteenth of those for coal plants equipped with the best available control technology (see table 8.1).

Opportunities for innovation are not exhausted. One option is to eliminate entirely the relatively capital-intensive steam turbine in a so-called Tophat® cycle that involves heating air exiting the compressor with turbine exhaust heat and spray intercooling during compression (van Liere, 1998). By injecting a mist of fine water particles into the compressor to cool the air during compression (using hot water produced from turbine exhaust heat), compressor work requirements are greatly reduced, and net turbine output and efficiency are increased.[14]

One study applying the Tophat® concept to a redesign of a modern aeroderivative gas turbine estimated that the gas turbine output would increase from 47 to 104 megawatts-electric, the efficiency would increase from 36.5 to 52.2 percent (almost to the level for the 400-megawatt-electric Frame 7H NGCC; see table 8.4), and NO_X emissions would be substantially reduced. The capital cost per kilowatt-electric for such a unit is expected to be less than for NGCCs (van Liere, 1998).[15]

In addition, during the next 10 years, system efficiencies might increase further to levels of nearly 60 percent, as technological advances make it possible for turbine inlet temperatures to move up to about 1,500 degrees Celsius, and various cycle configurations (for example, reheating and intercooling) are exploited (Chiesa and others, 1993).

TABLE 8.4. PERFORMANCE, GENERATION COSTS, AND CO_2 EMISSION RATES FOR ALTERNATIVE CONVENTIONAL FOSSIL FUEL POWER PLANTS

Performance, costs, and emission rates[a]	**Pulverised coal steam-electric plant with flue gas desulphurisation**	**Coal integrated gasifier combined cycle (IGCC) plant**		**Natural gas combined cycle (NGCC) plant**	
		Air-cooled turbine	**Steam-cooled turbine**	**Air-cooled turbine**	**Steam-cooled turbine**
Plant capacity (megawatts)	**500**	**500**	**400**	**506**	**400**
Efficiency (percent, higher heating value [HHV] basis)	**35.5**	**40.1**	**43.8**	**50.2**	**54.1**
Installed capital cost (dollars per kilowatt)	**1090**	**1320**	**1091**	**468**	**445**
Generation cost components (dollars per thousand kilowatt-hours)					
Capital charges[b]	17.9	21.7	17.9	7.7	7.3
Fixed operation and maintenance	2.3	2.8	3.0	2.3	2.3

Variable operation and maintenance	2.0	2.0	2.1	1.5	1.5
Fuel					
Typical U.S. fuel price[c]	10.1	9.0	8.2	19.4	18.0
Typical European fuel price[c]	17.2	15.3	14.0	22.9	21.3
Total generation cost (dollars per thousand kilowatt-hours)					
Typical U.S. fuel price[c]	32.3	35.5	31.2	30.9	29.1
Typical European fuel price[c]	39.4	41.8	37.0	34.4	32.4
CO_2 emission rate (grams of carbon per kilowatt-hour)[d]	**238**	**210**	**193**	**98**	**91**

a. Plant capacities, installed capital costs, operation and maintenance costs, and plant efficiencies are from Todd and Stoll (1997). Combined cycle plants with air-cooled and steam-cooled gas turbine blades involve use of General Electric Frame 7F (commercial) and Frame 7H (near commercial) gas turbines, respectively. b. Capital charges are calculated assuming a 10 percent discount rate, a 25-year plant life, and an insurance rate of 0.5 percent a year, and neglecting corporate income taxes, so that the annual capital charge rate is 11.5 percent. It is assumed that all power plants are operated at an average capacity factor of 80 percent. c. For the United States: coal and natural gas prices of $1.00 and $2.70 per gigajoule, respectively (average prices projected by the U.S. Energy Information Administration for electric generators in 2010; EIA, 1998a). For Europe: prices for

electric generators of $1.70 per gigajoule for coal (average for OECD countries in 1997) and $3.20 per gigajoule for natural gas (average for Finland, Germany, Netherlands, and United Kingdom for 1997). d. The carbon contents of coal and natural gas are assumed to be 23.4 kilograms of carbon per gigajoule and 13.7 kilograms of carbon per gigajoule, respectively.

If there are opportunities for using steam (for example, in support of an industrial process), hot gas turbine exhaust gases can be used to produce this steam in cogeneration configurations. Combined cycles can also be used for cogeneration - for example, by installing a back-pressure steam turbine instead of a condensing steam turbine with the gas turbine. With a back-pressure turbine, the high-quality steam produced from the gas turbine exhaust heat is first used to produce some electricity, and subsequently the lower quality steam discharged in the steam turbine exhaust is used for process applications. For such a system the ratio of produced electricity to process steam is higher than for a simple cycle gas turbine (figure 8.1).

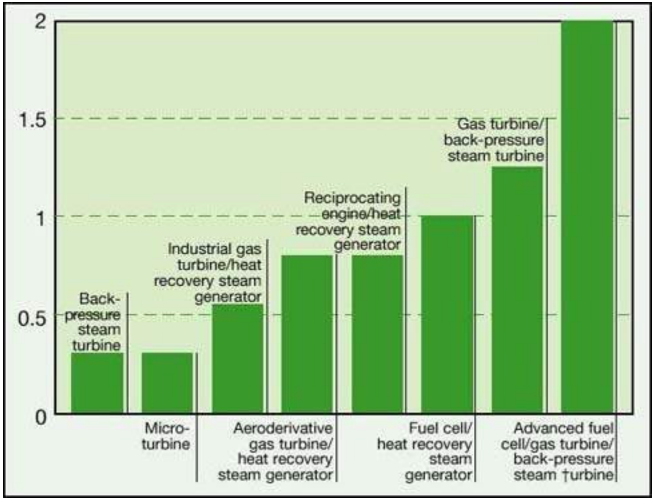

FIGURE 8.1. OUTPUT RATIOS OF POWER (KILOWATTS-ELECTRIC) TO HEAT (KILOWATTS-THERMAL) FOR ALTERNATIVE COGENERATION TECHNOLOGIES

Note: Ratios are for systems producing 10 bar steam. All steam turbines are back-pressure steam turbines with no steam condenser.

Source: Simbeck, 1999b.

Cogeneration is especially important in the near term for rapidly industrialising countries. Because these countries are in the early stages of building their infrastructure, their process-heat-intensive, basic-materials-processing industries are growing rapidly. Rapidly growing steam loads represent important resource bases for cogeneration, so that these industries have the potential of becoming major providers of clean, cost-competitive power. In this context, cogeneration systems employing gas turbines and combined cycles

equipped with back-pressure turbines provide several times as much electricity per unit of process steam as systems based on simple back-pressure turbines (figure 8.1). These and other cogeneration technologies characterised by high output ratios of electricity to steam (for example, reciprocating internal combustion engines and fuel cells) make it possible for cogeneration to play a far greater role in power generation than is feasible with steam-turbine technology.[16]

TABLE 8.5. COGENERATION VERSUS SEPARATE PRODUCTION OF ELECTRICITY AND STEAM USING NATURAL GAS COMBINED CYCLES

Rates of activity and costs	**Separate production facilities for electricity and steam**			**Cogeneration facility**
	Electricity	**Steam**	**Total**	
Power generation rate (megawatts-electric)	**400**	**-**	**400**	**400**
Process steam production rate, 10-15 bar (megawatts-thermal)	**-**	**400**	**400**	**400**
Natural gas input rate (terajoules per hour)	**2.66**	**1.77**	**4.43**	**3.48**
First Law efficiency (percent)	**54.1**	**81.1**	**64.9**	**82.8**
CO_2 emission rate (tonnes per hour)	**132**	**88**	**220**	**172**
Capital investment (millions of dollars)	**166**	**48**	**214**	**194**
Energy production cost (dollars per thousand kilowatt-hours)				
Capital	6.8	2.0	**-**	8.0
Operation and maintenance (4 percent of	2.4	0.7	**-**	2.8

capital cost per year)				
Fuel	18.0	12.0	-	23.5
Credit for cogenerated steam (at $14.7 per thousand kilowatt-hours of steam)	-	-	-	-14.7
Total (net) production cost (dollars per thousand kilowatt-hours)	**27.2**	**14.7**	**-**	**19.6**
Annual cost of energy (millions of dollars)	**76.3**	**41.2**	**117.5**	**55.0+41.2**
Cost of CO_2 emissions avoided (dollars per tonne of carbon)	**-**	**-**	**-**	**-$232**

> **Note: Based on calculations by Dale Simbeck, SFA Pacific. Engineering and contingencies and general facilities are each 10 percent of process capital equipment costs. The annual capital charge rate is 11.5 percent. The natural gas price is $2.70 per gigajoule (see note c, table 8.4). The annual average capacity factor equals 80 percent. The combined cycle plant assumed for both power only and cogeneration applications is the unit with steam-cooled gas turbine blades analysed in table 8.4.**

An example of cogeneration with NGCC technology and equal quantities of electric and steam power is described in table 8.5. For this system, the fuel required is a fifth less and the net cost of electricity is a quarter less per kilowatt-hour than for electricity and heat production in separate facilities. Moreover, net costs for CO_2 emissions reduction are strongly negative at - $230 per tonne of carbon relative to costs for systems that produce these products singly!

Cogeneration systems based on combined cycles and other high electricity and steam output ratio technologies will typically lead to far more electricity generated than the host factory can consume (Williams, 1978). Entrepreneurs will not be motivated to deploy such

technologies unless they are able to sell into the grid electricity produced at fair market rates. Existing electric-sector policies in many countries discourage such sales - for example, electric companies often will not purchase cogenerated power at market rates or will charge exorbitant fees for back-up service. But other countries have adopted policies encouraging cogeneration. In competitive power markets, cogenerators would typically do well (see table 8.5).

A final note: NGCC economic and environmental benefits in power and cogeneration markets are so attractive that countries with constrained natural gas supplies (such as China and India) should consider introducing NGCC plants as anchor users for natural gas supplies that might be introduced transnationally, using NGCC power generation and cogeneration revenues to underwrite pipeline and other gas infrastructure costs.

Oxygen-blown coal gasification and integrated gasifier combined cycle technologies. Gasification technology makes it possible to extend to coal the economic, thermodynamic, and environmental benefits of combined cycles in the form of IGCC power plants. Gasifiers can be oxygen-blown (O_2) or air-blown. All commercial units are O_2-blown, although some systems based on air-blown units are being demonstrated. The focus here is on systems with O_2-blown gasifiers; systems with air-blown gasifiers are discussed below.

Since the demonstration of IGCC technology with the 94-mega watt-electric Coolwater Project in southern California (1984 - 89), there has been much progress relating to its commercialisation. Table 8.6 lists five large commercial-scale coal IGCC plants around the world that produce electricity or electricity and steam (cogen-eration), as well as nine other large commercial projects that involve gasification of petroleum residues to coproduce electricity with H_2, syngas, or steam.[17] If all the syngas capacity in these 14 plants (9,825 megawatts-thermal) were dedicated to power generation, the equivalent electric generating capacity would be about 5,300 megawatts-electric.

Pollutant emission levels for coal IGCCs can be nearly as low as for NGCCs - much less than for coal steam-electric plants. Environmental damage costs associated with emission levels equivalent to those measured at the Buggenum plant in the Netherlands are less than 2 percent of such costs for average coal-fired power plants in the United States and about 10 percent of such costs for coal steam-electric plants equipped with the best available control technology (see table 8.1). Deep reductions in emissions are feasible because pollutants are recovered in concentrated form from the fuel gas (syngas) leaving the gasifier - undiluted by the large amounts of nitrogen from combustion air that are present in flue gases, from which air pollutants are recovered for conventional power plants.

IGCC technology also offers solid waste management advantages. Most direct combustion processes recover sulphur from flue gases as a nonmarketable wet scrubber sludge or as a dry spent sulphur sorbent (the by-product gypsum can be marketed). For such systems, solid wastes are more difficult to handle and market or dispose of, and volumes to be managed are two to three times those for IGCC systems, which recover a marketable elemental sulphur by-product.[18]

The cost of electricity for IGCC technology is somewhat higher than for coal steam-electric plants (compare Frame 7F IGCC and steam-electric plant costs in table 8.4) - when credit is not given for the environmental benefits, which would probably tip the balance decisively in favour of IGCC (see table 8.1). New turbine technology based on the use of steam-cooled turbine blades (Frame 7H technology) could tip the balance slightly in favour of IGCC, even without environmental credits (see table 8.4). But the direct economic benefits are likely to be too small to convince users to shift from familiar technology to any new technology, with all the attendant risks associated with its adoption. The user will take such risks only if forced to (for example, by environmental regulations) or because the economic benefits would be decisive.

Growing concerns about air quality are leading to increased interest in new fuels that have a higher degree of inherent cleanliness than traditional liquid fuels derived from crude oil.

O_2-blown coal gasification probably has a better chance of being launched in the market through applications other than power-only - for example, cogeneration. Table 8.7 illustrates the advantages offered by IGCC-based cogeneration. For this system, fuel requirements are reduced one fifth and the net electricity generation cost is reduced one fourth relative to electricity and steam production in separate facilities (as in the corresponding natural gas case - see table 8.5).

Of course, cogeneration strategies can also be pursued with conventional steam turbine technology. However, as illustrated by the calculation in table 8.8 for the same levels of electricity and process steam generation as in the IGCC case,[19] the fuel savings rate (5 percent) and the reduction in the net cost of electricity (9 percent) are far less than for the IGCC case. Moreover, a comparison of tables 8.7 and 8.8 shows that although there is little difference in efficiency and cost for IGCC and ultrasupercritical steam turbine technologies in producing electricity only, IGCC technology is a markedly better performer in cogeneration applications.

TABLE 8.6. LARGE COMMERCIAL GASIFICATION-BASED PROJECTS INVOLVING ELECTRICITY AS PRODUCT OR COPRODUCT

Location	Plant owner	Technology	Syngas out (megawatts - thermal)	Feedstock(s)	Product(s)	Start-up year

Spain	Repsol and Iberola	Texaco	1,654	Vacuum residues	Electricity	2004
Italy	SARLUX srl	Texaco	1,067	Visbreaker residues	Electricity, H_2	2000
Italy	ISAB Energy	Texaco	982	ROSE asphalt	Electricity, H_2	1999
France	Total France, EdF, and Texaco	Texaco	895	Fuel oil	Electricity, H_2	2003
Netherlands	Shell Nederland Raffinaderij BV	Shell	637	Visbreaker residues	Electricity, H_2	1997
Czech Republic	SUV and EGT	Lurgi Dry Ash	636	Coal	Electricity, steam	1996
United States	Public Service of Indiana	Destec	591	Bituminous Coal	Electricity	1995
Spain	Elcogas SA	PRENFLO	588	Coal, petcoke	Electricity	1997
United States	Motiva Enterprises LLC	Texaco	558	Fluid petcoke	Electricity, steam	1999
Italy	API Raffineria de Ancona S.p.A.	Texaco	496	Visbreaker residues	Electricity	1999
Netherlands	Demkolec BV	Shell	466	Bituminous Coal	Electricity	1994
United States	Tampa Electric Company	Texaco	455	Coal	Electricity	1996
United States	Exxon USA Inc.	Texaco	436	Petcoke	Electricity, syngas	2000

Singapore	Esso Singapore Pty. Ltd.	Texaco	364	Residual oil	Electricity, H_2	2000

Source: Simbeck and Johnson, 1999.

Once gasification technology is established in the market, a continuing stream of innovations can be expected to improve performance and reduce costs - because there are many opportunities (van der Burgt, 1998; Holt, 1999a). One way innovation will take place is by relatively passively incorporating continually improving gas turbine designs into IGCC systems - the benefits of which are illustrated by the shift from air-cooled to steam-cooled gas turbine blades in table 8.4. And if Tophat® turbines are developed (see above), such systems used with gasified coal would be both less capital-intensive and more energy-efficient than current IGCC systems - for example, van der Burgt and van Liere (1996) estimate that with such cycles overall efficiency would increase to about 50 percent.

Specific IGCC-related improvements might also be made. For example, new gasifiers are needed that are well suited for coals with high ash content (typical of many coals in China, India, and South Africa) and for low-rank coals (which are abundant world-wide; see chapter 5), because commercially available entrained-flow gasifiers are not well suited for such coals. Fluidised-bed gasifiers are good candidates for these coals; such gasifiers would also be better suited for handling most biomass and waste as co-feedstocks than are entrained-flow gasifiers. Such technology, in the form of the High Temperature Winkler gasifier, was demonstrated with brown coal at a plant in Berrenrath, Germany, where the syngas was used to produce methanol (Simbeck and others, 1993). An IGCC project based on the High Temperature Winkler gasifier for coal fines has been proposed for construction in the Czech Republic (Holt, 1999b).

One research and development focus is technology to clean gases at high temperatures to

reduce thermodynamic losses associated with thermal cycling of gases exiting the gasifier.[20] Such technology is being pursued largely because it is necessary for successful development of IGCC systems based on air-blown gasifiers and advanced pressurised fluidised-bed combustion systems (see below). However, hot gas clean-up is not necessary for IGCC systems with O_2-blown gasifiers. The technology is challenging (especially to realise the low emission levels achievable with present cold-gas cleanup), and potential economic benefits are modest even if positive, especially because coal prices are low and declining (Simbeck, 1995; Williams, 1999b).

Despite coal IGCC technical successes, there are few opportunities for deploying the technology in the industrialised world, where electricity demand is growing slowly, and where the NGCC is the technology of choice wherever there is a need for new power supplies and natural gas is available. The best potential opportunities for IGCC technology are in China and other developing countries where natural gas is not readily available and rapid growth in coal use is expected. There, IGCC technology could have enormous positive impacts in reducing local and regional air pollution, while substantially improving efficiencies and reducing greenhouse gas emissions. To make initial deployment of IGCC technology economically interesting to such countries, the first installations might be in cogeneration or polygeneration (see below) configurations. As in the case of NGCC cogeneration, the key to unlocking the cogeneration potential offered by IGCC technology is policies that make competitive electricity prices available to these producers for the electricity they wish to sell into electricity grids.

Encouraging competitive power markets could help put industry on a path to fossil energy with near-zero emissions by helping launch syngas-based polygeneration activities.

Small engines for cogeneration (reciprocating engines and microturbines). IGCC cogeneration technologies are suitable for deployment at scales of hundreds of megawatts; NGCC cogeneration technologies can be deployed at scales from a few up to hundreds of megawatts. But many small factories, commercial buildings, and apartment buildings would be good candidates for clean, gas-based cogeneration if appropriate technologies were available at scales from less than 100 kilowatts-electric to a few megawatts. Both reciprocating engines and microturbines show promise as near-term technologies for cogeneration at such scales.

From June 1997 through May 1998, world-wide sales of reciprocating engines for stationary power markets totalled about 5,100 units (9.6 gigawatts-electric of total capacity) - a gain of five times from 10 years earlier (Wadman, 1998). More than half of the units will be for continuous service.[21] Although most units will use oil, 13 percent will use natural gas or will be capable of using dual fuels. Gas applications might expand markedly under increasingly competitive power market conditions.

For spark-ignited engines, shifting to natural gas involves significant de-rating. Compression-ignition engines can also be converted to gas, either by adding a spark plug or by using a liquid spark - a small amount of diesel fuel for ignition. The latter approach is preferable with regard to both first cost and efficiency. Compression-ignition engines with liquid sparks bring to natural gas applications the low cost and high efficiencies of these engines, with much less de-rating. Recent advances have reduced liquid spark requirements for dual-fuel engines to 1 percent of system fuel requirements for larger engines. Such engine generator sets are commercially available at scales of 1 - 16 megawatts-electric with lower heating value (LHV) efficiencies of 39 - 42 percent.

Prices for both spark-ignited and dual-fuel engine generator sets (for equipment only) for the capacity range under 1 megawatt-electric typically lie in the range $425 - 600 per

kilowatt-electric - prices that do not include the costs for heat recovery equipment for cogeneration. Operation and maintenance costs for reciprocating engines are typically significantly higher than for combustion turbines. Reciprocating engines can be used for cogeneration by recovering both high-quality heat from the engine exhaust and low-quality heat from the engine jacket cooling water. Like gas turbines and combined cycles, reciprocating engines are attractive for such applications because of their high electricity-heat output ratios (see figure 8.1). Some reciprocating engine vendors offer complete cogeneration package systems. Very small-scale systems (under 100 kilowatts-electric) sell in the United States for $1,500 - 2,000 per kilowatt-electric. The engines for such systems last only 3 - 4 years, but replacement engines cost only $75 per kilowatt-electric.

TABLE 8.7. COGENERATION VERSUS SEPARATE PRODUCTION OF ELECTRICITY AND STEAM USING COMBINED CYCLE AND COAL GASIFICATION TECHNOLOGIES

Rates of activity and costs	Separate production facilities for electricity and steam			Cogeneration plant
	IGCC plant	Industrial boiler	Total	
Power generation rate (megawatts-electric)	400	-	400	400
Process steam production rate, 10-15 bar (megawatts-thermal)	-	400	400	400
Coal input rate (terajoules per hour)	3.20	1.65	4.85	3.88
First Law efficiency (percent)	45.1	87.2	59.4	74.3
CO_2 emission rate (tonnes per hour)	274	142	416	333
Capital investment (millions of dollars)	453	197	650	537
Annual energy production cost (millions of dollars per year)				

Capital	52.19	22.69	74.88	61.86
Operation and maintenance (4 percent of capital cost per year)	18.12	7.88	26.00	21.48
Fuel	22.44	11.57	34.01	27.21
Total annual energy cost	92.75	42.14	134.89	110.55
Specific cost of energy (dollars per thousand kilowatt-hours)	**For power:**	**For steam:**		**For power:**
Gross cost	33.1	15.0	-	39.4
Credit for steam coproduct	-	-	-	-15.0
Net cost	33.1	15.0	-	24.4

Note: Based on calculations by Dale Simbeck, SFA Pacific. Engineering plus contingencies are 10 percent of process capital equipment costs; general facilities are 10 percent of process capital equipment costs. The annual capital charge rate is 11.5 percent. The coal price is $1.00 per gigajoule (see note c, table 8.4). The annual average capacity factor is 80 percent. Both the stand-alone integrated gasifier combined cycle (IGCC) power plant and the cogeneration plant use a Destec O_2-blown coal gasifier coupled to a combined cycle with steam-cooled gas turbine blades.

TABLE 8.8. COGENERATION VERSUS SEPARATE PRODUCTION OF ELECTRICITY AND STEAM USING STEAM TURBINE AND PULVERIZED COAL COMBUSTION TECHNOLOGIES

Rates of PCC activity and costs	**Separate production facilities for electricity and steam**			**Cogeneration plant**
	PCC power	**Industrial**	**Total**	

	plant	**boiler**		
Power generation rate (megawatts-electric)	**400**	**-**	**400**	**400**
Process steam production rate, 10-15 bar (megawatts-thermal)	**-**	**400**	**400**	**400**
Coal input rate (terajoules per hour)	**3.39**	**1.65**	**5.04**	**4.68**
First Law efficiency (percent)	**42.4**	**87.2**	**57.1**	**61.6**
CO_2 emission rate (tonnes per hour)	**291**	**142**	**433**	**402**
Capital investment (millions of dollars)	**453**	**197**	**650**	**612**
Annual energy production cost (millions of dollars per year)				
Capital	52.19	22.69	74.88	70.50
Operation and maintenance (4 percent of capital cost per year)	18.12	7.88	26.00	24.48
Fuel	23.77	11.57	35.34	32.82
Total annual energy cost	94.08	42.14	136.22	127.8
Specific cost of energy (dollars per thousand kilowatt-hours)	**For power:**	**For steam:**		**For power:**
Gross cost	33.6	15.0	-	45.6
Credit for steam coproduct	-	-	-	-15.0
Net cost	33.6	15.0	-	30.6

Note: Based on calculations by Dale Simbeck, SFA Pacific. Engineering plus contingencies are 10 percent of process capital equipment costs, as are general facilities. The annual capital charge rate is 11.5 percent. The coal price is $1.00 per

> **gigajoule (see note c, table 8.4). The average capacity factor is 80 percent. The pulverized coal combustion (PCC) plant is an ultrasupercritical unit for the stand-alone power plant and a sub-critical unit for the cogeneration plant.**

Air pollutant emissions, especially NO_x, are a concern. Uncontrolled gas engines produce significant CO and non-methane hydrocarbon emissions; however, relatively low-cost oxidation catalytic converters can control such emissions. Most lean-burning, spark-ignited natural gas engines and micro-liquid-spark, dual-fuel engines can achieve NO_x emission of 1.4 grams per kilowatt-hour (100 parts per million by volume at 15 percent O_2) - about 15 times the emission rate for large modern NGCCs with state-of-the-art NO_x controls (see table 8.1). Some vendors now offer systems with half this level of emissions but at an energy efficiency penalty of about 1 percentage point. In some areas (for example, many parts of the United States), NO_x emission regulations will severely limit deployment of reciprocating engines for stationary power markets at scales from 100 kilowatts-electric to 2 megawatts-electric.

Operation of reciprocating engines on town gas (that is, syngas) is also feasible and would be an especially attractive option for natural-gas-poor, coal-rich regions. There town gas could be produced from coal at centralised facilities along with syngas for other poly-generation activities and piped up to 30 kilometres to various distributed cogeneration facilities. The air quality benefits of such gas-based technologies relative to direct coal combustion would be especially important in countries such as China, where coal is used for heating in small, inefficient boilers equipped with little or no air pollution control equipment. However, such systems would not be pollution free. Air emission concerns would be similar to those for reciprocating engines operated on natural gas, except that NO_x emissions might be higher because of higher adiabatic flame temperatures.

Reciprocating engines can also be adapted to small-scale operations in rural areas using either biogas (from anaerobic digesters) or producer gas generated by thermochemical gasification of biomass (see Mukunda, Dasappa, and Srinivasa, 1993; chapters 7 and 10).

Efforts under way to improve reciprocating engine markets for stationary power include the five-year Advanced Reciprocating Engine Systems (ARES) programme - being carried out by a consortium of U.S. manufacturers, the U.S. Department of Energy, the Gas Research Institute, and the Southwest Research Institute. ARES is targeting development of an advanced gas engine with an efficiency of 50 percent (LHV basis) and a NO_x output of 5 parts per million by volume (including catalytic aftertreatment if necessary).

There is growing confidence among scientists that underground sequestration of CO_2 will prove to be a major option for mitigating climate-change risks.

The microturbine is a gas turbine just entering the market for applications at scales less than 100 kilo-watts-electric. Its development recently got a boost as a result of its being chosen as a cruise missile engine. One vendor has already launched the technology in the market, and several other aerospace firms are getting ready to market it for stationary power applications. Promoters project that it will do well in new highly competitive distributed power markets (Craig, 1997).

The system involves a low-pressure ratio (3 to 4) gas turbine and compressor mounted on a single shaft.[22] The most promising models available are air cooled and have variable

speed generators (the output of which is rectified and converted electronically to the alternating-current line frequency), no gear-box, no lubricating oil requirements, and only one moving part. Turbine blades are not cooled, turbine inlet temperatures are modest (840 degrees Celsius), but engine speeds are high - 80,000 revolutions a minute or more. Conversion efficiencies with natural gas fuelling are 25 percent (LHV basis) at full power output - far less than for large reciprocating engines but comparable to reciprocating engine generator set efficiencies at scales of tens of kilowatts-electric. Efficiency falls off at part load - to 75 percent of the efficiency at full output when output falls to a third of the peak level (Campanari, 1999).

Although electric efficiencies are not especially high, the technology offers four attractive features:

- **Potentially low capital costs in mass production, because of the simple design.**
- **Low maintenance costs - probably considerably lower than for reciprocating engines, because of the low combustion temperature and the simple design's expected higher reliability.**
- **Suitability for cogeneration, because all waste heat is of high quality, in the form of hot (230 - 270 degrees Celsius) air.**
- **The possibility of low NO_x emissions without stack gas controls.[23]**

The microturbine faces competition from both reciprocating engines and fuel cells. Maintenance and air quality issues will be important in determining the outcome of competition with reciprocating engines. At scales of hundreds of kilowatts-electric, it will be very difficult for microturbines to compete in efficiency with reciprocating engines. Moreover, if the ARES programme meets its NO_x emissions reduction target, the

competition from reciprocating engine technology will be strong at all sizes for which such emissions can be realised.

At the small scales (under 100 kilowatts-electric) that are the focus for market development, the major competition will be from fuel cells - for example, the proton exchange membrane (PEM) fuel cell (see below). Fuel cells will be more efficient in producing electricity from natural gas and will have lower air pollutant emissions. But microturbines will be better performers in providing heat for cogeneration than PEM fuel cells, for which the waste heat quality is low. And microturbines will probably be valued more by utilities as peaking units than PEM fuel cells operated on natural gas, which cannot so readily be dispatched to serve peaking needs.

Microturbines could have great appeal in markets where low-cost gaseous fuels are available - for example, producer gas derived from low-cost crop residues in rural areas of developing countries (chapter 10). They also appear to be well suited for use as bottoming cycles for hybrid cycles that employ pressurised molten carbonate or solid oxide fuel cells as topping cycles (Campanari, 1999; Kartha, Kreutz, and Williams, 1997).

Fuel cells for stationary power and cogeneration. The fuel cell converts fuel into electricity electrochemically, without first burning it to produce heat (Kartha and Grimes, 1994). Fuel cells have attractive features for electricity markets characterised by increasing competition and environmental regulations: high thermodynamic efficiency, low maintenance requirements, quiet operation, zero or near-zero air pollutant emissions without exhaust-gas controls, and high reliability. Fuel cells are likely to be economically viable even in small-scale (100 kilowatts-electric or less) applications. Its properties make it possible to site systems in small, unobtrusive generating facilities close to end users.

Such distributed power sources make cogeneration designs economically attractive and

offer the potential of reducing capital outlays for electricity transmission and distribution equipment (Hoff, Wenger, and Farmer, 1996). Low-temperature phosphoric acid fuel cells (PAFCs) and proton exchange membrane fuel cells (PEMCs) are well suited for combined heat and power applications in small- to medium-scale commercial and residential buildings, providing domestic hot water and space heating and cooling (Little, 1995; Dunnison and Wilson, 1994). Developers of high-temperature molten carbonate fuel cells (MCFCs) and solid-oxide fuel cells (SOFCs) target medium- to large-scale industrial applications.

The PAFC, developed largely in Japan and the United States, is the only commercial fuel cell. Several hundred PAFC power plants (mostly 200-kilowatt-electric natural-gas-fuelled units) are operating. Accumulated experience has demonstrated that fuel cell power plants can be made to operate reliably. Costs are high, however, and whether they can be reduced enough with volume production to make the PAFC widely competitive is uncertain.

Because of recent technological advances, substantial U.S., European, and Japanese activities are seeking to accelerate commercialisation of the PEMFC for residential and commercial building cogeneration markets (Dunnison and Wilson, 1994; Little, 1995; Lloyd, 1999) as well as for transportation (see below). Several companies are developing residential PEMFC combined heat and power systems (Lloyd, 1999). Ballard Generation Systems plans to begin selling 250-kilowatts-electric system for commercial buildings by 2003 - 04; Plug Power is focussing on smaller (less than 35-kilowatt-electric) units and plans to install the first residential units by 2001.[24] In initial applications it is expected that most systems would use mainly existing natural gas infrastructure and, like PAFCs, process natural gas at the point of use in an external fuel processor into an H_2-rich gas the fuel cell can use.

The best chances for making small fuel cells competitive are in markets that value

electricity highly (for example, in residential or other buildings, where produced electricity must be less costly than the retail rate) and where fuel cell waste heat can be used effectively. Space heating and cooling markets are not well matched to PEMFC capabilities; space heating demand is seasonal with enormous variation in the heating season; and the operating PEMFC temperature (80 degrees Celsius) is too low to use waste heat for heat-driven air conditioners.

However, domestic hot water demand often provides a good match - demand is fairly level year-round, and the PEM operating temperature is well suited for domestic hot water. Especially promising opportunities are where the fuel cell is sized to meet the demand for domestic hot water, so that very little waste heat is discarded. If the PEMFC size were increased to meet a larger fraction of the electrical load, it would become more and more difficult to compete, because more and more of the waste heat would have to be discarded, reducing the credit (per kilowatt-hour of electricity) for waste heat utilisation.

The economic prospects are best for apartment buildings, hotels, and hospitals, where a centralised building-scale PEM fuel cell system serves power and hot water needs throughout. It would be more difficult for such systems to compete at the level of single-family dwellings for currently expected PEMFC economies of scale (Kreutz and Ogden, 2000).

The high operating temperatures for MCFCs (600 - 650 degrees Celsius) and SOFCs (1,000 degrees Celsius) make them well suited for cogeneration, including applications that use the waste heat to operate heat-driven air conditioners. They also offer the option of using directly natural gas or syngas derived through gasification from coal or other feedstocks without an external fuel processor - because these gases can be reformed (using waste heat from fuel cell operation) and shifted on the anode into an H_2-rich gas the fuel cell can easily use - leading, potentially, to higher efficiency, simplified operation, and increasing reliability. (But having an external reformer offers the flexibility of being able to switch

relatively easily to operation on alternative fuels.)

The two principal vendors for MCFCs have been Energy Research Corporation and MC Power. Energy Research Corporation units operate at atmospheric pressure with internal reforming; MC Power units operate at pressure but with an external reformer. A 1.8-megawatt-electric demonstration plant based on Energy Research Corporation technology was built and operated on natural gas beginning in April 1996 in Santa Clara, California; a peak efficiency of 40 percent was achieved. Because of various difficulties, the unit was operated for only 4,000 hours and was dismantled in March 1997. In March 1999 Energy Research Corporation put into operation a 250-kilowatt-electric demonstration unit at its Danbury, Connecticut, headquarters. In 1997 MC Power operated a 250-kilowatt-electric cogeneration unit at the Naval (now Marine Corps) Mirimar Air Station in San Diego, California. Unable to raise new funding for research and development, MC Power went out of business in March 2000.

SOFCs offer the potential for high efficiency, low cost, and potentially long operating lifetimes (Bakker, 1996). The main uncertainties concern manufacturing costs and durability in operation as a result of the fact that SOFCs are made of ceramics. Although the cost of the materials in the ceramics is inherently low ($7 - 15 per kilowatt-electric; Goldstein, 1992), fabrication of ceramics is difficult and costly. Moreover, there are risks that the ceramic components will develop cracks during operation as a result of thermal cycling.

Siemens Westinghouse, the leading SOFC developer, has focussed on a tubular design and has deployed seven fully integrated, automatically controlled, packaged SOFC systems as experimental field units. The largest of these is a 100-kilowatt-electric natural-gas-fuelled cogeneration system deployed in the Netherlands in early 1998. The system has realised extremely low pollutant emissions - 0.2 parts per million by volume of NO_x and undetectable levels of sulphur dioxide (SO_2), CO, and unburned hydrocarbons (Veyo,

1998).

The tubular design facilitates manufacture and realisation of properly operating seals, but it is uncertain how low costs can become in mass production. Planar designs that operate at lower temperatures (800 degrees Celsius)[25] seem promising with regard to both high efficiency (55 - 70 percent on natural gas, LHV basis) and capital cost in mass production ($700 - 800 per kilowatt-electric at a scale of 500 kilowatts-electric; Chen, Wright, and Krist, 1997). But such designs require considerable more research and development.

In the 1970s and 1980s it was expected that high-temperature fuel cells would eventually be able to compete with conventional power generating technologies at a wide range of scales - including large central-station power plants as well as cogeneration plants of all sizes. But the enormous success of gas turbines and combined cycles dampened the prospects for large-scale fuel cell applications during the early 1990s - when it became apparent that the marginal efficiency gains offered by fuel cells over combined cycles would not be able to justify the expected higher capital costs - except in small-scale operations (1 megawatt-electric or less). However, since the early 1990s two developments have once more brightened the prospects for high-temperature fuel cells for larger-scale installations.

The first is a hybrid concept that offers both higher efficiency and lower capital cost. A hybrid would be made up of a high-temperature fuel cell topping cycle and a gas turbine or a steam turbine or gas turbine - steam turbine combined cycle bottoming cycle. A high-temperature fuel cell operated on natural gas or syngas will utilise only 80 - 90 percent of the gas energy. The chemical energy remaining in the hot anode exhaust gases can be burned to generate more electricity in a bottoming cycle. Modelling carried out at the Electric Power Research Institute indicates that a 56 percent efficient natural-gas-fuelled SOFC combined with a regenerative gas turbine bottoming cycle could lead to a system efficiency of 71 percent (Bakker, 1996) - efficiencies well above the levels that can be

realised with gas turbine - steam turbine combined cycles. Because the cost per kilowatt-electric of the bottoming cycle will typically be less than the than the cost per kilowatt-electric for the fuel cell itself, the overall capital cost for the hybrid will be less than for a purebred fuel cell.

The second new development is related to the fact that pressurised high-temperature fuel cells offer an option for low-cost CO_2 recovery and disposal as a response to climate change concerns. The concept is related to the fact that CO_2 is available at high partial pressure in the anode exhaust of pressurised SOFCs or MCFCs in highly concentrated form. To illustrate, consider operation of a pressurised SOFC on syngas (mainly CO and H_2) derived from coal through O_2-blown gasification. Both the CO and the H_2 react in the anode directly with O_2 (transported across the electrolyte from the cathode as an oxygen ion) to form CO_2 and H_2O. If the 10 - 20 percent of the unconverted CO and H_2 exiting the anode is then burned in O_2 for use in a bottoming cycle,[26] the gaseous product will be a mixture of CO_2 and H_2O, from which the H_2O can easily be removed by cooling and condensation. Moreover, if the bottoming cycle is a steam turbine, the CO_2 can be recovered for disposal at relatively high pressure, leading to low costs for further pressurising the CO_2 to the level needed for disposal. Recognising the value of this strategy, Shell announced in July 1999 plans to develop and market with Siemens Westinghouse SOFC technology capable of disposing of CO_2 in this manner.[27]

BOX 8.2. DEEP OCEAN SEQUESTRATION OF ANTHROPOGENIC CARBON DIOXIDE

The ocean, containing 40,000 gigatonnes of carbon (relative to 750 GtC in the atmosphere), represents the largest potential sink for anthropogenic CO_2; disposing in the ocean of an amount of CO_2 that would otherwise lead to a doubling of the atmosphere’s content would thus increase the ocean concentration by less than 2 percent. On a 1,000-year time scale, more than 90 percent of today's anthro-pogenic emissions will be transferred to the oceans through a slow, natural process. The basic idea of ocean sequestration of CO_2 is to inject CO_2 directly into the deep ocean to accelerate this process and reduce both peak atmospheric CO_2 concentrations and their rate of increase.

For a large fraction of injected CO_2 to remain in the ocean, injection must be at great depths. This is because CO_2 would be a gas above 800 metres and a liquid below 800 metres. Liquid CO_2 is negatively buoyant relative to ordinary seawater only below 3,000 metres. Liquid CO_2 is negatively buoyant relative to seawater saturated with CO_2 only below 3,700 metres. And at injection depths of about 500 metres or more, a CO_2-seawater mixture (depending on the relative compositions) can lead to formation of a CO_2 hydrate, which is about 10 percent denser than seawater.

A consensus is developing that the best near-term strategy would be to discharge CO_2 at depths of 1,000 - 1,500 metres, which can be done with existing technology. A major uncertainty that requires more research for clarification relates to the sequestration efficiency (the fraction of the CO_2 that remains in the ocean) of injection at such depths (see, for example, Brewer and others, 1999). Another approach, aimed at maximising sequestration efficiency, is to inject liquid CO_2 into a deep sea-floor depression, forming a stable deep lake at a depth of 4,000 metres - an approach that is technologically challenging with current technology. A simple and feasible but very costly option is to release dry ice from a surface ship. Another approach is to create a dense CO_2-seawater mixture at a depth of 500 - 1,000 metres and cause it to form a sinking-bottom gravity current - an approach that has raised many environmental impact concerns.

On a global scale, both climate change and other environmental impacts of ocean disposal (for example, increased ocean acidity) are positive. But on a local scale, there are considerable environmental concerns arising largely as a result of the increased acidification near the points of injection - for example, impacts on non-swimming marine organisms residing at depths of 1,000 metres or more.

Japan has the world's most active ocean sequestration research programme, led by the Research Institute of Innovative Technology for the Earth and the Kansai Environmental Engineering Centre, and funded at an annual level of more than 10 million dollars.

Although the deep ocean has been the most-discussed option for CO_2 disposal, much more research is needed to better understand the security, costs, and environmental impacts of various ocean disposal schemes (Turkenburg, 1992). In addition, the viability of ocean storage as a greenhouse gas mitigation option hinges on social and political as well as technical, economic, and environmental considerations. The public is generally cautious regarding ocean projects.

Source: Herzog, 1999b.

Decarbonisation and carbon dioxide sequestration strategies for power generation systems. Because of climate change concerns, increasing attention has been given in recent years to strategies for extracting energy from fossil fuels without releasing CO_2 into the atmosphere. The issues involved concern the capacity, security, and cost of alternative CO_2 disposal options and the costs of separating the CO_2 from fossil energy systems and preparing it for disposal.

The options for CO_2 sequestration include both the deep ocean and geological reservoirs. Although ocean disposal has received the most attention (box 8.2), large uncertainties in its prospects (Turkenburg, 1992) have led to a shift of focus in recent years to give more attention to geological (underground) storage of CO_2, in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and gas recovery), in deep coal beds (in conjunction with coal bed methane recovery), and in deep saline aquifers.

CO_2 injection for enhanced oil recovery (Blunt, Fayers, and Orr, 1993), enhanced gas recovery (van der Burgt, Cantle, and Boutkan, 1992; Blok and others, 1997), and enhanced recovery of deep coal bed methane (Byrer and Guthrie, 1999; Gunter and others, 1997; Stevens and others, 1999; Williams, 1999a) might become profitable focuses of initial efforts to sequester CO_2. Enhanced oil recovery using CO_2 injection is well-established technology; one project that began in 2000 in Saskatchewan, Canada, is injecting yearly up to 1.5 million tonnes of CO_2, which is transported 300 kilometres to the injection site from a synthetic natural gas plant in North Dakota (see below).

Sequestration in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded (van der Burgt, Cantle, and Boutkan, 1992; Summerfield and others, 1993). One estimate of the prospective global sequestering capacity of such reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources is 100 GtC for oil fields and 400 GtC for gas fields (Hendriks, 1994). Other estimates are as low as 40 GtC for depleted oil fields and 90 GtC for depleted gas fields, plus 20 GtC associated with enhanced oil recovery (IPCC, 1996a). The range is wide because reservoir properties vary greatly in their suitability for storage, and because oil and gas recovery may have altered the formations and affected reservoir integrity. Much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas.

> A fierce global competition is underway to accelerate the development of fuel cell vehicles.

Deep aquifers are much more widely available than oil or gas fields. Such aquifers underlie

most sedimentary basins, the total areas of which amount to 70 million square kilometres (two-thirds onshore and one-third offshore), more than half the 130-million-square-kilometre land area of the inhabited continents. Some sedimentary basins offer better prospects for CO_2 storage than others (Hitchon and others, 1999; Bachu and Gunter, 1999). To achieve high storage densities, CO_2 should be stored at supercritical pressures (more than about 75 times atmospheric pressure), which typically requires storage at depths greater than 800 metres. The aquifers at such depths are typically saline and not effectively connected to the much shallower (typically less than 300-metre) sweet-water aquifers used by people. If aquifer storage is limited to closed aquifers with structural traps, the potential global sequestering capacity is relatively limited - about 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from burning fossil fuel at the current rate.

However, if structural traps are not required for effective storage, potential aquifer storage capacity might be huge; estimates range from 2,700 GtC (Omerod, 1994) to 13,000 GtC (Hendriks, 1994). For comparison, estimated remaining recoverable fossil fuel resources (excluding methane hydrates) contain about 5,600 GtC (see table 5.7). A growing body of knowledge indicates that many large horizontal open aquifers might provide effective storage[28] if the CO_2 is injected far enough from reservoir boundaries that it dissolves in the formation water or precipitates out as a mineral as a result of reactions with the surrounding rock before migrating more than a few kilometres towards the basin boundaries (Bachu, Gunter, and Perkins, 1994; Gunter, Perkins, and McCann, 1993; Socolow, 1997). The relatively new idea that large horizontal aquifers can provide effective sequestration has contributed to growing confidence among scientists that underground sequestration of CO_2 will prove to be a major option for mitigating climate-change risks (Holloway, 1996; Socolow, 1997; PCAST Energy Research and Development Panel, 1997).

Experience with aquifer disposal will be provided by two projects involving injection into nearby aquifers of CO_2 separated from natural gas recovered from CO_2-rich gas reservoirs. One is a Statoil project begun in 1996 to recover 1 million tonnes of CO_2 a year from the Sleipner Vest offshore natural gas field in Norway (Kaarstad, 1992). The second, which will commence in 10 years, will involve the recovery of more than 100 million tonnes a year (equivalent to 0.5 percent of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71 percent of the reservoir gas is CO_2) (IEA, 1996).

Extensive historical experience with underground gas storage contributes to the growing scientific confidence in the reliability of geological reservoirs for storing CO_2. And regulations that have been evolving for underground gas storage provide a good basis for defining the issues associated with formulation of regulations for CO_2 storage (Gunter, Chalaturnyk, and Scott, 1999).

More research, field testing, modelling, and monitoring are needed to narrow the uncertainties relating to CO_2 storage in geological reservoirs. From a policy perspective, it is particularly important to understand better potential effective storage capacities on a region-by-region basis so that energy and environmental planners will have a better understanding of the overall potential for fossil fuel decarbonisation with CO_2 sequestration as an option for dealing with climate change. Getting such important information is not likely to be especially costly. For example, Stefan Bachu of the Alberta Research Council has estimated that obtaining a reasonable estimate of the geological CO_2 storage capacity of Canada would cost $14 million (Gunter, 1999). The cost is relatively low because geological surveys have collected an enormous amount of relevant data during the past 100 years, and many more relevant data from industrial sources are available from regulatory bodies.

Public acceptability issues are paramount. Fuel decarbonisation with CO_2 sequestration is unfamiliar to most people as a strategy for dealing with the climate change challenge. What will public attitudes be? The scientific community has a major responsibility to inform the public debates on the various issues relating to safety and environmental impacts. Much can be learned from both natural events (Holloway, 1997) and from the extensive historical experience with use of CO_2 injection for enhanced oil recovery and with underground gas storage (Gunter, Chalaturnyk, and Scott, 1999). But more research is needed to clarify the issues.

An optimistic note on which to end this discussion: in the sections that follow, it will be shown that those advanced fossil energy technologies offering the potential for CO_2 disposal at the least costs are also characterised by near-zero emissions of air pollutants.

TABLE 8.9. ALTERNATIVE TECHNOLOGIES FOR REDUCING CO_2 EMISSIONS FROM 400-MEGAWATT-ELECTRIC COAL PLANTS

Technology	Efficiency (percent, HHV)	Capital cost (dollars per kilowatt)	Generation cost (dollars per thousand kilowatt-hours)	O_2 requirements (tonnes per hour)	CO_2 emissions (grams of carbon per kilowatt-hour)	Cost of avoiding CO_2 emissions (dollars per tonne of carbon)
Ultrasupercritical pulverised coal steam turbine plant						
Reference, CO_2 vented	43.1	1,114	33.0	0	196	-

CO_2 recovery from flue gasses	34.3	1,812	52.2	0	36.8	134
O_2 firing, CO_2 recovery from flue gasses	32.0	1,661	52.8	339	0	111
Pressurised fluidised-bed combustion plant						
Reference, CO_2 vented	43.1	1,114	33.0	0	196	-
O_2 firing, CO_2 recovery from flue gasses	35.4	1,675	51.6	307	0	104
Integrated gasifier - combined cycle plant						
Reference, CO_2 vented	45.9	1,114	32.5	80	184	-
Cold CO_2 recovery from synthesis gas	36.1	1,514	47.9	108	23.9	96
Warm CO_2 recovery from synthesis gas (advanced technology)	41.5	1,466	44.5	94	20.4	73
H_2-O_2 Rankine cycle plant: Cold CO_2 recovery from synthesis gas (advanced technology)	40.5	1,622	48.4	259	6.1	90
Solid oxide fuel cell (SOFC) plant						

H_2-fueled SOFC - gas turbine - steam turbine plant, warm CO_2 recovery from synthesis gas (advanced technology)	45.7	1,461	43.3	85	19.1	65
SOFC - steam turbine plant, CO_2 recovered from anode exhaust burned with O_2 (advanced technology)	44.3	1,427	43.1	114	6.8	60

Note: Based on calculations by Dale Simbeck, SFA Pacific. Engineering and contingencies are 10 percent of process capital equipment costs; general facilities are 10 percent of process capital equipment costs. The annual capital charge rate is 11.5 percent. The coal price is $1.00 per gigajoule. The annual average capacity factor is 80 percent. All options involving CO_2 separation and disposal include the cost of compressing the separated CO_2 to 135 bar plus a cost of $5 per tonne of CO_2 ($18 per tonne of carbon) for pipeline transmission and ultimate disposal.

People are likely to be more willing to accept fuel decarbonisation with CO_2 sequestration as a major energy option if the technology also offers near-zero emissions than if they view it as a way to sustain a dirty energy system - away from which they would rather evolve.

Table 8.9 presents performance and cost calculations (developed in a self-consistent manner across options) for eight alternative technologies and strategies for CO_2 removal

and disposal for coal-fired power systems - variants of calculations developed earlier by Simbeck (1999c). Four options are based on current or near-term (before 2005) technologies. The other four (labelled advanced technology) require considerable technological development. The H_2-O_2 Rankine cycle plant involves producing H_2 through coal gasification and burning it with O_2 in a Rankine cycle - a technology proposed by Westinghouse researchers (Bannister and others, 1996; Bannister, Newby, and Yang, 1997, 1998). The turbine in this system looks like a gas turbine in the high-pressure stages but a steam turbine at the condensing end - because the combustion of H_2 in O_2 leads to the production of only steam. If there were a market for the turbine used in this system, it could probably be developed in 2010 - 20. The SOFC options require commercialisation of SOFC power technology, which developers expect to take place before 2010. The two warm gas recovery options require the development of relatively challenging advanced gas separation technologies, which could be commercial by 2015.

The CO_2 separation and disposal options are compared with three reference technologies for power generation without CO_2 removal and disposal: an ultrasupercritical steam-electric plant (see below), a pressurised fluidised-bed combustion plant (see below), and an IGCC plant (the Frame 7H option described in table 8.4). Identical capital costs are assumed for these reference plants: Not only is this a reasonable approximation, but also this assumption helps clarify cost differences for CO_2 separation and disposal among alternatives.[29] The cost of avoided CO_2 emissions for each case is calculated relative to the least costly option in the table (the reference IGCC case, with CO_2 venting).

The first CO_2 recovery option involves CO_2 scrubbing from the stack gases of an ultrasupercritical steam-electric plant using an amine solution (flue gas scrubbing). The cost of avoiding CO_2 emissions and the power generation cost penalty are relatively high ($134 per tonne of carbon and $0.020 per kilowatt-hour), largely because of the high cost

penalties associated with recovering CO_2 from the stack gases, where its concentration and partial pressure are low (15 percent and 0.15 bar, respectively).

The second option uses atmospheric pressure O_2 rather than air as oxidant, and recycles the separated CO_2 back to the ultra supercritical steam plant combustor. This strategy greatly increases the partial pressure of CO_2 in the flue gas. Cost penalties are comparable to those for flue gas recovery because of the large quantities of costly O_2 required. The third option is for a pressurised fluidised-bed combustion unit that uses pressurised O_2 as the oxidant instead of pressurised air. This further increases the CO_2 partial pressure in the flue gas and reduces CO_2 removal costs; however, because pressurised O_2 is more costly than O_2 at atmospheric pressure, the savings relative to the ultra-supercritical steam-electric cases is modest.

The air pollution emissions issue will be in centre stage during the competition between fuel cell and hybrid internal combustion engine vehicles to be car of the future.

The five remaining options - which have avoided CO_2 emission costs that are much lower than for the first three - are for systems involving O_2-blown gasifiers. The first, cold CO_2 recovery from synthesis gas for IGCC plants, is based on existing CO_2 recovery technology. This option starts with gasification to produce syngas (mainly CO and H_2). The syngas is reacted with steam in shift reactors to convert CO into H_2 and CO_2. Subsequently, CO_2 is separated out for disposal, and the H_2-rich fuel gas is burned in the

gas turbine combustor.[30] This option has the least cost penalties of all the near-term options ($96 per tonne of carbon and $0.015 per kilowatt-hour). The low cost is realised largely because, when CO_2 is recovered from the shifted syngas in an IGCC, its concentration is high (33 percent), as is its partial pressure (more than 10 bar). The advanced technology option labelled warm CO_2 recovery from synthesis gas for IGCC plants, could - if successfully developed - reduce avoided CO_2 emission costs by a fourth relative to the cold gas recovery option. For the advanced technology option labelled cold CO_2 recovery from synthesis gas for an H_2-O_2 Rankine cycle, the H_2-O_2 turbine capital cost is expected to be relatively low, and the efficiency of converting H_2 into electricity high. However, the system requires large quantities of costly O_2. As a result this system would not improve on the least costly current technology option - cold CO_2 recovery from synthesis gas for an IGCC plant.

The last two entries depend on the successful development of SOFC technology. The penultimate entry also depends on the success of warm-gas separation technology. The last entry is the least costly of the advanced technology options - involving recovery of CO_2 at pressure from the anode exhaust (see above). This technology would provide electricity from coal with only 3 percent of the CO_2 emissions for the conventional coal steam-electric plant at a generation cost of $0.043 per kilowatt-hour, for an avoided CO_2 emission cost of $60 per tonne of carbon.[31] This is about $0.01 per kilowatt-hour more than the cost of electricity from a coal-fired power plant today with no CO_2 removal and sequestration. This is consistent with findings by a group at the Massachusetts Institute of Technology (MIT) Energy Laboratory that, with advanced IGCC technology (expected to be commercially available by 2012), the cost penalty for decarbonisation and sequestration would be less than $0.01 per kilowatt-hour (Herzog, 1999a).

An implicit assumption for these calculations is that a new coal plant is the least costly option - for example, the calculations are appropriate for coal-rich, natural-gas-poor countries. If natural gas were available, the cost of CO_2 emissions avoided by CO_2 recovery and disposal at a coal plant would typically be higher. Table 8.10 presents calculations, also based on Simbeck (1999c), that illustrate the situation for near-term (before 2005) technology when NGCCs and coal IGCCs are competing, and emission reductions of 90 percent are considered for both. The IGCC option is the IGCC with cold CO_2 recovery from table 8.9. For NGCCs, two CO_2 separation-and-disposal options are considered. The least costly option involves scrubbing CO_2 from flue gases.

TABLE 8.10. THE COST OF ELECTRICITY FROM COAL AND NATURAL GAS WITH AND WITHOUT CO_2 SEQUESTRATION, BASED ON NEAR-TERM TECHNOLOGIES

Rates of activity and costs	**USC steam[a]**	**Natural gas-fired combined cycle[b]**			**Coal IGCC**	
CO_2 sequestered?	**No**	**No**	**Yes**	**Yes**	**No**	
CO_2 separation method	**-**	**-**	**FGS[c]**	**NG→H_2c**	**-**	**Syr**
Efficiency (percent, HHV basis)	**43.1**	**54.0**	**45.7**	**42.2**	**45.9**	
Emission rate (grams of carbon	**196**	**90**	**15.7**	**11.6**	**184**	

per kilowatt-hour)						
CO_2 disposal rate (grams of carbon per kilowatt-hour)	**-**	**-**	**91**	**104**	**-**	
Capital cost (dollars per kilowatt)	**1,114**	**416**	**907**	**918**	**1,114**	
Generation cost[d] (dollars per thousand kilowatt-hours)						
Capital	18.30	6.83	14.90	15.08	18.30	
Operation and maintenance	6.35	2.37	5.17	5.24	6.35	
Fuel	$8.35 \bullet P_C$	$6.67 \bullet P_{NG}$	$7.88 \bullet P_{NG}$	$8.53 \bullet P_{NG}$	$7.84 \bullet P_C$	9
CO_2 disposal (at $5 per tonne of	-	-	1.66	1.90	-	

CO$_2$)^e Total generation cost^f	$24.65+8.35 \bullet P_C$	$9.20+6.67 \bullet P_{NG}$	$21.73+7.88 \bullet P_{NG}$	$22.22+8.53 \bullet P_{NG}$	$24.65+7.84 \bullet P_C$	37.8
at 1998 U.S. fuel prices	34.6	23.8	39.5	41.5	34.0	
at 2020 U.S. fuel prices	32.0	29.7	45.9	48.4	31.6	
Avoided CO$_2$ emissions cost, relative to same technology without separation and disposal (dollars per tonne of carbon, for 2020 U.S. fuel prices)^g	**-**	**-**	**219**	**236**	**-**	
Electricity cost (dollars per thousand kilowatt-hours), for 2020 U.S.	**74.9**	**49.3**	**49.3**	**51.0**	**71.8**	

fuel prices and $219 tax per tonne of carbon						

a. For a 400-megawatt-electric, pulverised-coal, ultrasupercritical steam-electric plant; see table 8.9. b. Based on an analysis developed in Simbeck (1999c); coal IGCC technologies are the same as for reference and cold CO_2 recovery cases in table 8.9. c. FGS = flue gas scrubber; for $NG \rightarrow H_2$ case, natural gas (NG) is converted to H_2 using an O_2-autothermal reformer. d. Annual capital charge rate = 11.5 percent; annual operation and maintenance cost = 4 percent of capital cost; P_C = coal price, P_{NG} = natural gas price (dollars per gigajoule). e. To account for pipeline transmission and ultimate disposal costs. f. For 1998: P_C = $1.19 per gigajoule; P_{NG} = $2.26 per gigajoule, average U.S. prices for electric generators (EIA, 1999b). For 2020: P_C = $0.88 per gigajoule; P_{NG} = $3.07 per gigajoule, average U.S. prices projected for electric generators in the Energy Information Administration's reference scenario (EIA, 1998a). g. Avoided cost = (generation cost with sequestration minus generation cost without sequestration) divided by (emissions without sequestration minus emissions with sequestration).

Even though removal of twice as much CO_2 per kilowatt-hour is required for the IGCC case, the cost penalty per kilowatt-hour of CO_2 separation and disposal is not greater than for the NGCC case. This counterintuitive result arises because scrubbing CO_2 from NGCC *flue gases* is more capital- and energy-intensive than recovering CO_2 from IGCC *fuel gas.* H_2 could also be made from natural gas by reforming. But as shown, with current technology doing so would not be less costly than scrubbing flue gas, because the gain in

reduced cost by avoiding the flue gas scrubber would be offset by the added costs for reformer and shift reactors.[32]

One result of the analysis shown in table 8.10 is that - for the CO_2 recovery-and-disposal cases and 2020 U.S. fuel prices - the costs of generating electricity from natural gas and coal are about the same ($0.046 - 0.047 per kilowatt-hour). The findings of Herzog (1999a) - who considered improvements in the technologies relative to the cases presented in table 8.10 and which he projected would be commercial by 2012 - indicate that this cost parity between coal and natural gas systems is likely to hold even when technological improvements are taken into account for natural gas as well as coal technologies.[33]

The last row in table 8.10 shows the electric generating costs with a carbon tax high enough to induce NGCC power generators (as well as coal IGCC power generators) to separate and dispose of CO_2. This tax ($220 per tonne of carbon) is 2.3 times the carbon tax needed if there were no competition from natural gas. The cost of power generation (including the carbon tax) would be $0.05 per kilowatt-hour for all options except coal plants without CO_2 separation and disposal. With the advanced technologies considered by Herzog (1999a), the carbon tax needed to induce CO_2 recovery and disposal for NGCC plants would be less ($170 versus $70 per tonne of carbon for coal IGCC plants).

The technologies considered here for CO_2 recovery and disposal do not exhaust the possibilities. A class of advanced technologies that offers considerable promise of increasing system efficiency and reducing CO_2 removal costs for both natural gas and coal power systems involves using inorganic membranes that are highly permeable to H_2 but not other gases. If such membranes were applied to natural gas combined cycles, they might make it possible to carry out simultaneously steam reforming, water gas shifting,

and H_2 separation in a single vessel. Continuous H_2 removal by the membrane might make it feasible to carry out reforming reactions at temperatures low enough that gas turbine exhaust heat could be used to provide the needed heat (Moritsuka, 1999). (The application of such technologies to coal systems is discussed below.)

Advanced fuels for transportation and other applications

This section discusses the prospects for using advanced fuels to satisfy the sustainable development objectives of keeping fuels affordable, increasing energy security, and evolving towards near-zero emissions of both air pollutants and greenhouse gases. The focus here is mainly on transport fuels that can be derived from syngas, with some reference to synthetic cooking fuels. (The prospects for synthetic fuels derived by direct coal liquefaction are discussed in the next section below.) This discussion of transport fuels is presented in the context of the associated vehicle technologies and the challenges posed by various fuel-vehicle combinations.

Oxygenated fuels: the current focus. U.S. fuel improvement efforts have focussed on reducing levels of benzene (an extremely carcinogenic aromatic compound) in gasoline and on adding oxygenates such as methyl tertiary butyl ether (MTBE) to gasoline to reduce CO emissions and inhibit photochemical smog formation, while maintaining octane ratings that would otherwise fall as a result of lead removal. Although oxygenates are effective in reducing CO emissions and maintaining octane rating, they offer negligible benefits in reducing atmospheric ozone formation (Calvert and others, 1993).

MTBE derived from methanol (MeOH) is widely added to gasoline in volumetric quantities up to 15 percent to help control CO emissions. About 30 percent of the U.S. population lives in areas where MTBE is in regular use; U.S. production levels reached more than 6 million tonnes in 1995. But MTBE use in the future is likely to be severely limited. In July 1999 the U.S. Environmental Protection Agency announced that it would act to greatly

reduce the use of MTBE in reformulated gasoline, and in December 1999 the California Air Resources Board banned the use of MTBE in reformulated gasoline in California beginning in 2003.

The shift from MTBE is taking place not only because its air quality benefits appear to be marginal, but also because it is extremely soluble and persistent in water, and humans may be experiencing prolonged exposure to it through tap water. Although it is not especially harmful to humans at typical exposure levels, it imparts a bitter taste and solvent-like odour to water that it contaminates - and human taste and odour thresholds are extremely low (40 parts per billion). MTBE enters drinking water through leaks in gasoline tanks or spills into surface water or groundwater. Although tank leaks also release benzene and many other aromatic and non-aromatic compounds, MTBE tends to migrate faster than other contaminants and is likely to be at the leading edge of a travelling plume (Stern and Tardiff, 1997).

Alcohols. Alcohols (methanol and ethanol) have attracted considerable interest as alternative automotive fuels, especially in Brazil and the United States. The production from biomass of ethanol through biological processes and methanol through t hermochemical processes that begin with thermochemical gasification are discussed in chapter 7.

MeOH can be produced from any carbonaceous feedstock through processes that begin with syngas production - for example, from natural gas through steam reforming, from coal through O_2- blown gasification, or from biomass through steam gasification (Williams and others, 1995). Nearly all MeOH is produced from low-cost sources of natural gas, which are often available at remote sites where a natural gas pipeline infrastructure has not been established. Because MeOH is an easily transported liquid, its production from remote gas sources provides a means of exploiting such resources. Most MeOH is used as a chemical feedstock. Its use as a fuel has mainly been for MTBE manufacture. In

addition, modest amounts have been used directly in blends with gasoline for cars. With conventional technology, the cost of making it from coal is much greater than from natural gas, because the added capital cost for gasification generally cannot be adequately compensated for by the lower cost of coal relative to natural gas.

Although the use of alcohol fuels in vehicles with internal combustion engines can lead to reduced oil dependence, it is now generally believed that alcohol fuels - especially when blended with gasoline and used in flexible-fuel internal combustion engine vehicles - offer little or no air quality advantages other than lower CO emissions (Calvert and others, 1993). Moreover, reformulated gasoline can meet or surpass the air pollution reductions of alcohol-gasoline blends (CTOFM, 1991). With MeOH, CO emissions would be reduced, and emissions of volatile organic compounds would be less problematic than for gasoline. NO_x emissions would probably not be reduced, however. Ethanol offers fewer air quality benefits than MeOH and may produce more ozone per carbon atom (Calvert and others, 1993).

Emissions from alcohol-fuelled fuel cell vehicles would be a tiny fraction of the emissions from gasoline-fuelled internal combustion engine vehicles. Moreover, the use of alcohols in fuel cell vehicles would lead to marked improvements in fuel economy relative to their use in internal combustion engine vehicles. Several auto manufacturers plan to launch fuel cell vehicles in the market using MeOH as fuel (see below).

If MeOH were to become widely used as an energy carrier for transportation, a concern is its toxicity through direct ingestion, absorption through the skin, or ingestion as a result of drinking methanol-contaminated groundwater.[34] Detailed risk assessments indicate that toxicity is not likely to be a significant concern in routine use, although it might be problematic for accidents involving large spills (Health Effects Institute, 1987). In the case of groundwater contamination, risks are generally much less than for MTBE, because in most situations MeOH would degrade quickly. But oil companies - having been burned

by recent decisions to ban MTBE after having made enormous investments in MTBE production, and concerned about liability issues relating to MeOH's toxicity - might be reluctant to make major investments in MeOH, especially if there are promising non-toxic, clean alternative fuels.

The need for a policy framework for transport fuels and engines. The discussions of MTBE and alcohol fuels highlight the lack of a coherent, consistent policy framework for developing advanced fuels and engines for transportation. Closely related to these discussions is the emerging view that environmental regulations are not focussed on the most important pollutants.

Recent studies indicate that by far the greatest costs associated with health impacts arising from transport-related air pollutant emissions are those from fine particles (chapter 3) - both those emitted from vehicles directly and nitrate particles formed in the atmosphere from NO_x emissions. Spadaro and Rabl (1998) estimate that relative to the costs associated with fine particles the health costs posed by CO emissions are negligible, and health costs associated with ozone formation are modest (see table 8.2). It thus appears that concerns about NO_x and particulate emissions will shape future technological choices for fuels and engines.

Besides the lack of a properly focused environmental policy, low oil prices and gasoline taxes also provide no market incentive in the United States for fuel-efficient cars. There the trend has been towards an increasing market share of fuel-guzzling sport utility vehicles - exacerbating concerns about energy supply security and emissions of air pollutants and CO_2.

One auspicious development from Japan is recent commercialisation of a gasoline-fuelled car powered by a hybrid of an internal combustion engine and a battery. This hybrid offers fuel economy twice that of conventional cars with internal combustion engines. Their high

efficiency and the fact that they can be operated most of the time near their optimal operating points make it feasible to achieve much lower emissions with gasoline hybrids than with conventional internal combustion engine vehicles.

Advanced hybrid vehicles are being developed under the U.S. Partnership for a New Generation of Vehicles (PNGV), a government-industry initiative that seeks to develop production-ready prototypes that will get 80 miles a gallon (34 kilometres a litre) by 2004 (NRC, 1998). Because this goal is three times the fuel economy of existing cars, emphasis is being given to hybrids based on compression ignition engines (specifically, compression-ignition direct-injection, or CIDI, engines), which are more fuel efficient than spark-ignited hybrids. The CIDI hybrid and the fuel cell car (see below) are the leading contenders to meet PNGV goals for the car of the future.

But the ambitious PNGV research and development programme is not complemented by incentives to introduce such fuel-efficient vehicles into the market. Moreover, unlike the situation with gasoline hybrids, there is no strong air quality driver for advancing CIDI hybrids. To the contrary, air pollution mitigation challenges are far more daunting for compression-ignition than for spark-ignited engines (see table 8.2). In early 2000 DaimlerChrysler introduced a prototype CIDI hybrid car developed under the PNGV that got 72 miles a gallon (30.6 kilometres a litre). Although this car met the air quality standards in effect in 1993, when the PNGV was launched, the current design cannot meet the standards that will be in effect in 2005, when such cars might first be produced on a commercial basis.

There is also a need for better coordination between development activities for fuels and engines. There are needs not only for new fuels but also new engines that are optimised for these fuels.

Syngas-derived fuels for compression-ignition engines and other applications.

Compression-ignition engines play major roles in transport, where they are used for buses, trucks, and trains, and in some regions (such as Europe) for cars as well. Such engines are especially important for developing and transition economies, where in 1996 diesel fuel accounted for half of all transport fuel (relative to a fifth in the United States; EIA, 1999a). The efficiency benefits offered by these engines will be even more important in the future as transport demand grows. For example, the World Energy Council's 1995 market rules scenario projects that the number of cars will grow by six times between 1990 and 2020 in developing and transition economies, from 95 million to 580 million (WEC, 1995). Both improved engines and improved fuels will be needed to help mitigate the challenges that such growth poses for energy supply security, air quality, and greenhouse gases.

CIDI engines are promising advanced technologies for improving efficiency, especially when used in hybrid vehicles. Concerns about CIDI hybrids include high costs and whether they will be able to meet expected tougher regulatory goals for NO_x and particulate emissions. In its fourth review of the PNGV, the U.S. National Research Council urged the PNGV to consider shifting emphasis in its CIDI research to non-hybrid versions, in light of the high costs of hybrids (NRC, 1998).

Among the leading candidate fuels for addressing the challenges posed by compression-ignition engines are synthetic middle distillates (SMDs) and dimethyl ether (DME). SMDs are straight-chain hydro-carbon fuels (paraffins and olefins) produced through the Fischer-Tropsch (F-T) process. The F-T process begins with the production of syngas from a carbonaceous feedstock - for example, from natural gas through steam reforming or partial oxidation, or from coal through O_2-blown gasification and even from biomass through gasification.

SMDs are well suited for use in compression-ignition engines, in part because of their high

cetane numbers.[35] Moreover, they contain no benzene, other aromatic compounds, or sulphur. Measurements have shown 13 - 37 percent reductions in particulate emissions and 6 - 28 percent reductions in NO_x emissions relative to operation on diesel fuel (Sirman, Owens, and Whitney, 1998; Schaberg and others, 1997; Norton and others, 1998). Even greater reductions would be likely if the engines were optimised for use with these fuels, including exhaust gas aftertreatment as well as engine modifications.

The well-established F-T technology for making SMDs can be used with either natural gas or coal as feedstock. Near-term activities will be focussed on use of low-cost supplies of natural gas. Despite high production costs, Shell's small, natural-gas-based Malaysian SMD plant (12,500 barrels a day; see below) made money by selling SMDs for making blends with ordinary diesel fuel to enable compression-ignition engines to meet the tough air pollution standards in California and by selling high-value coproducts (for example, waxes) in niche markets.[36]

Efforts to reduce costs will involve building larger plants. For example, Exxon is considering building a large (50,000 - 100,000 barrels a day) SMD plant in Qatar as a strategy for developing that country's vast low-cost gas supplies (Fritsch, 1996; Corzine, 1997). Reducing costs will also involve pursuing polygeneration strategies (see the next section).

Another candidate fuel for compression ignition engines is DME, an oxygenated fuel that can be produced from any carbonaceous feedstock by a process that begins, as in the case of MeOH and SMDs, with syngas production. Today DME is produced (150,000 tonnes a year) mainly to provide a replacement for chlorofluoro-carbons as a propellant in aerosol spray cans. Not only does DME not harm the ozone layer (it degrades quickly in the troposphere), but it is non-toxic and non-carcinogenic.

For compression ignition engine applications, DME offers a high cetane number and the

potential to achieve low emissions without tailpipe emission controls. Because DME has no carbon-carbon bonds, soot emissions from its combustion are zero. In addition, NO_X emissions can be substantially less than with ordinary diesel fuel. Truck engine emission tests show that NO_X emission are down 55 - 60 percent and particle emissions are down 75 percent relative to diesel fuel. Residual particle emissions appear to come from the lubricating oil (Fleisch and Meurer, 1995).

DME has also been identified as an especially promising clean cooking fuel (Chen and Niu, 1995). Its wide availability in developing countries could dramatically mitigate the horrendous air pollution health impacts from burning biomass and coal for cooking (chapters 3 and 10). The main drawback of DME is that at atmospheric pressure it boils at - 25 degrees Celsius, so it must be stored in moderately pressurised (9-bar) tanks (much as liquid petroleum gas, which boils at - 42 degrees Celsius, is stored). Thus infrastructure challenges would be more demanding in shifting to DME than in shifting to SMDs. But this is not a show-stopper.

> The fossil energy system can evolve in ways consistent with sustainable development objectives if public policies guide a high rate of innovation toward super-clean fossil energy technologies

Today DME is produced by catalytic dehydration of MeOH and is thus more costly than MeOH. However, an advanced single-step process under development by Haldor Topsoe would make it possible to make DME from natural gas at higher efficiency and less cost than for MeOH. Haldor Topsoe and Amoco have estimated that if DME were produced in large plants in areas with low-cost natural gas, it could be produced at costs not much

higher than comparable diesel prices, taking into account the environmental benefits of DME (Hansen and others, 1995). Also promising is the outlook for DME production in polygeneration systems (see below).

It is very likely that fuel strategies will have to be complemented by engine strategies to realise needed low levels of emissions from compression-ignition engines. The possibilities include the use of high-pressure fuel injectors, of catalytic converters to reduce the soluble organic fraction of the particulates, and of particulate traps positioned in the engine exhaust stream - along with some means of burning off the collected particulate matter, most of which is soot (Walsh, 1995; 1997). One new twist is that new engines and exhaust controls being developed to dramatically reduce the mass concentration of particles, in response to tightening air quality regulations, seem to give rise to larger number concentrations (Kittelson, 1998; Bagley and others, 1996; Kruger and others, 1997; Mayer and others, 1995).[37] The larger number concentrations might be problematic because of growing concerns about health impacts of small particle pollutants - although the public health implications of this emissions shift are unclear because of the paucity of data.

Although there are many promising technological opportunities to reduce emissions from compression-ignition engines, it is not clear if advanced fuel and engine technological strategies will be adequate to address air quality challenges fully. The fuel cell is a competing technology for addressing these challenges (see below).

Polygeneration strategies for synthetic fuels production. Just as cogeneration can lead to improved economics relative to production of electricity and process steam in separate facilities (see tables 8.5 and 8.7), so can synthetic fuel production economics be improved by polygeneration - including as coproducts various combinations of electricity, steam, town gas, and chemicals. Especially promising are strategies that coproduce electricity and synthetic fuels from syngas in once-through processes - in which syngas is passed

once through a reactor to produce synthetic fuel, and the unconverted syngas is burned to produce electricity in a combined cycle.

Once-through processes are well matched to new liquid-phase reactors. With conventional gas-phase reactors, relatively low conversions are achieved in a single syngas pass through the reactor, so that syngas is usually recycled to achieve higher conversions using recycling equipment that is typically capital- and energy-intensive. New liquid-phase reactors - which involve bubbling syngas through a column of heavy oil in which catalysts appropriate to the desired conversion are suspended - offer outstanding heat removal capability in controlling highly exothermic reactions and can achieve high conversions in a single pass, making recycling less attractive and once-through conversion more attractive.

TABLE 8.11. TRIGENERATION VERSUS SEPARATE PRODUCTION OF METHANOL AND COGENERATION USING COAL GASIFICATION TECHNOLOGY

Rates of activity and costs	Separate production facilities for MeOH and cogeneration			Trigeneration plant
	MeOH plant	Cogeneration plant	Total	
Power generation rate (megawatts-electric)	-	400	400	400
Process steam production rate, 10-15 bar (megawatts-thermal)	-	400	400	400
Methanol production rate (megawatts-thermal)	400	-	400	400
Coal input rate (terajoules per hour)	2.46	3.88	6.34	6.46
First Law efficiency (percent)	58.6	74.3	68.1	66.9
CO_2 emission rate (tonnes per hour)	211	333	544	555

Capital investment (millions of dollars)	**379**	**537**	**916**	**700**
Annual energy production cost (millions of dollars per year)				
Capital	43.66	61.86	105.52	80.64
Operation and maintenance (4 percent of capital cost per year)	15.16	21.48	36.64	28.00
Fuel	17.25	27.21	44.46	45.30
Total annual energy cost	76.07	110.55	186.62	153.94
Specific cost of energy (dollars per thousand kilowatt-hours)	**For MeOH:**	**For power:**		**For MeOH:**
Gross cost	27.1	39.4	-	54.9
Credit for steam coproduct	-	-15.0	-	-15.0
Credit for electricity coproduct	-	-	-	-24.4
Net cost	27.1 ($0.12 per litre)	24.4	-	15.5 ($0.07 per litre)

Note: Based on calculations by Robert Moore (formerly Air Products), building on Dale Simbeck's analysis in table 8.7 for a gasification-based cogeneration plant, assuming Air Products' liquid-phase reactor for MeOH production. Engineering plus contingencies and general facilities are each 10 percent of process capital equipment costs. The annual capital charge rate is 11.5 percent. The coal price is $1 per gigajoule (see note c, table 8.4). The annual average capacity factor is 80 percent.

TABLE 8.12. QUADGENERATION VERSUS SEPARATE PRODUCTION OF TOWN GAS AND

TRIGENERATION USING COAL GASIFICATION TECHNOLOGY

Rates of activity and costs	**Separate production facilities for towngas and trigeneration**			**Quadgeneration plant**
	Towngas plant	**Trigen plant**	**Total**	
Power generation rate (megawatts-electric)	**-**	**400**	**400**	**400**
Process steam production rate, 10-15 bar (megawatts-thermal)	**-**	**400**	**400**	**400**
Methanol production rate (megawatts-thermal)	**-**	**400**	**400**	**400**
Syngas production rate (megawatts-thermal)	**400**	**-**	**400**	**400**
Coal input rate (terajoules per hour)	**1.89**	**6.46**	**8.35**	**8.36**
First Law efficiency (percent)	**76.0**	**66.9**	**69.0**	**68.9**
CO_2 emission rate (tonnes per hour)	**163**	**555**	**718**	**718**
Capital investment (millions of dollars)	**228**	**700**	**928**	**783**
Annual energy production cost (millions of dollars per year)				
Capital	26.27	80.64	106.91	90.20
Operation and maintenance (4 percent of capital cost per year)	9.12	28.00	37.12	31.32
Fuel	13.25	45.30	58.55	58.63
Total annual energy cost	48.64	153.94	202.58	180.15

Specific cost of energy (dollars per thousand kilowatt-hours)	For town gas:	For MeOH:		For town gas:
Gross cost	17.3	54.9	-	64.2
Credit for steam coproduct	-	-15.0	-	-15.0
Credit for electricity coproduct	-	-24.4	-	-24.4
Credit for MeOH coproduct	-	-	-	-15.5
Net cost	17.3 ($4.80 per gigajoule)	15.5 ($0.07 per litre)	-	9.3 ($2.60 per gigajoule)

Note: Based on calculations by Robert Moore (formerly Air Products), building on Dale Simbeck's analysis in table 8.7 for a gasification-based cogeneration plant, assuming Air Products' liquid-phase reactor for MeOH production. Engineering plus contingencies and general facilities are each 10 percent of process capitalequipment costs. The annual capital charge rate is 11.5 percent. The coal price is $1 per gigajoule (see note c, table 8.4). The annual average capacity factor is 80 percent.

To illustrate polygeneration based on coal-derived syngas, table 8.11 presents calculations for the coproduction of 400 megawatts each of MeOH, electricity, and process steam (trigeneration) from coal by adding extra syngas production capacity to the system described in table 8.7 for the cogeneration of 400 megawatts each of electricity and process steam. Table 8.12 presents calculations for the coproduction of 400 megawatts each of town gas, MeOH, electricity, and process steam (quadgeneration) from coal by adding still more syngas production capacity to the system described in table 8.11.[38] Costs for MeOH produced in liquid-phase reactors through once-through processes have been extensively analysed (Drown and others, 1997), and the technology is relatively well developed.[39]

Consider first the trigeneration system (see table 8.11). In contrast to the cogeneration system (see table 8.7) from which it is evolved, trigeneration does not lead to further fuel savings, but capital cost savings are large. Values assumed for coproducts are $0.0150 a kilowatt-hour for steam (its cost in a stand-alone boiler) and $0.0244 a kilowatt-hour for electricity (its cost in gasification-based cogeneration). Thus the incremental cost for methanol is $0.07 a litre ($4.30 a gigajoule) - compared with $0.012 a litre for MeOH produced from coal in a stand-alone plant. This MeOH cost is less than the average U.S. refinery (wholesale, untaxed) gasoline price in 1997 ($5.10 a gigajoule).

In the quadgeneration example, extra syngas is produced as town gas for distribution by pipelines to nearby users - for example, small-scale cogeneration facilities based on compression-ignition reciprocating engines with pilot oil (see above). Note that, whereas producing 400 megawatts of town gas in a dedicated gasification facility would cost $4.80 a gigajoule, the cost of adding an extra 400 megawatts of syngas capacity for town gas purposes at a trigeneration plant would cost instead $2.60 a gigajoule, because of the scale economy effect. For comparison, the average 1997 U.S. city-gate price of natural gas was $3.30 a gigajoule.

The trigeneration and quadgeneration calculations illustrate the importance of building large, centralised, coal-syngas-based production systems to serve distributed markets for the products. The synthetic liquid fuels produced can be readily transported to vast markets of remote users. Likewise, the electricity coproduct can serve large markets if the polygenerator is able to sell the electricity coproduct into the electric grid at market rates. In contrast, the extra syngas produced as town gas can be transported economically only up to distances of 10 - 30 kilometres from the production facility. But even in this case, the markets served could be large if the centralised coal conversion plant were located near cities where large numbers of small factories, commercial buildings, and apartment buildings could be served.

Urban siting for these facilities can be considered for gasification-based coal conversion systems because of the very low levels of air pollutant emissions that can be realised (see table 8.1). The major restriction imposed by the market for the strategy illustrated in tables 8.7, 8.11, and 8.12 is that the process steam demand is defined by the needs of the host and is thus very site-specific, with limited overall market opportunity. Thus the coproduction of process steam should be considered an important initial market for helping to launch coal gasification technology in the market rather than a large, unconstrained market opportunity. Polygeneration strategies will often make economic sense, even without the benefit of the process steam coproduct.

Coal-based polygeneration strategies will be especially important for coal-rich, natural-gas-poor countries like China. Although most polygeneration activity relating to syngas production is taking place in industrialised countries, it is also getting under way in some developing countries (table 8.13 - and table 8.6 above). Consider that - although China has deployed no modern O_2-blown gasifiers in the power sector - it is already using many such gasifiers in the chemical process industries.[40] Such industries might provide better homes for launching IGCC technologies on the market in China and many other countries than would the electric power industry as it now exists.

Simbeck and Johnson (1999) point out that gasification-based polygeneration is being carried out in some countries without subsidy at refineries and chemical plants, because the economics are inherently attractive. They also point out that polygeneration based on gasification of refinery residues will often be more attractive economically than for coal. Such residues often have high sulphur content and are priced low. Moreover, capital costs tend to be lower - for example, because solids handling, crushing, and feeding systems are not needed. In addition, the generally lower levels of ash in heavy oils means less fouling of syngas coolers, so that lower cost designs might be employed (Todd and Stoll, 1997). Yet much of the technology is the same as for coal, so that this early experience will be

helpful in buying down the cost of the technology as experience accumulates, making the technology increasingly attractive for coal as well.

In contrast to the use of large-scale polygeneration systems for improving the economics of coal-based synthetic fuels, the focus for natural-gas-based polygeneration is likely to be on making synfuels production more attractive at small scales - by enabling the production of easy-to-transport liquid fuels from remote, small-scale sources of cheap natural gas.

To illustrate, consider the economics of the coproduction of F-T liquids and electricity from natural gas using liquid-phase reactors in a once-through process. Choi and others (1997) found that such systems producing about 8,800 barrels a day of liquids - plus 84 megawatts-electric of by-product power from remote gas - would be able to provide liquid fuels at a cost competitive with liquid fuels derived from $19 a barrel crude oil, assuming that the by-product electricity is sold for $0.03 a kilowatt-hour. The authors also found that such a plant would be competitive with a F-T plant employing recycling technology producing five times as much synfuels output. Thus, as long as crude oil prices do not plunge much below $20 a barrel, gas liquids derived from natural gas through liquid-phase reactor technology in once-through configurations are likely to be cost-competitive.

TABLE 8.13. LARGE COMMERCIAL GASIFICATION-BASED PROJECTS THAT DO NOT GENERATE ELECTRICITY

Location	Plant owner	Technology	Syngas out (megawatts-thermal)	Feedstock(s)	Product(s)	Start-up year
South Africa	Sasol-II	Lurgi Dry Ash	4,130	Sub-bituminous coal	F-T liquids	1977

South Africa	Sasol-III	Lurgi Dry Ash	4,130	Sub-bituminous coal	F-T liquids	1982
United States	Dakota Gasification Company	Lurgi Dry Ash	1,545	Lignite, refinery residues	Synthetic natural gas	1984
Malaysia	Shell MDS Sdn. Bhd.	Shell	1,032	Natural gas	Middle distillates	1993
Germany	Linde AG	Shell	984	Visbreaker residues	Methanol, H_2	1997
South Africa	SASOL-I	Lurgi Dry Ash	911	Sub-bituminous coal	F-T liquids	1955
United States	Unspecified	Texaco	656	Natural gas	MeOH, CO	1979
Taiwan, China	Chinese Petroleum Corp.	Texaco	621	Bitumen	H_2, CO	1984
Germany	Hydro Agri Brunsbttel	Shell	615	Heavy vacuum residues	NH_3	1978
Germany	VEBA Chemie AG.	Shell	588	Vacuum residues	NH_3, MeOH	1973
Czech Republic	Chemopetrol a.s.	Shell	492	Vacuum residues	NH_3, MeOH	1971
Brazil	Ultrafertil S.A.	Shell	451	Asphalt residues	NH_3	1979

China	Shanghai Pacific Chemical Corp.	Texaco	439	Anthracite coal	MeOH, town gas	1995
China	Shanghai Pacific Chemical Corp.	IGT U-Gas	410	Bituminous coal	Fuel gas, town gas	1994
India	Gujarat National Fertilizer Corp.	Texaco	405	Refinery residues	NH_3, MeOH	1982
Portugal	Quimigal Adubos	Shell	328	Vacuum residues	NH_3	1984

Source: Simbeck and Johnson, 1999.

The benefits of this technology are related not just to the product price but also to natural gas resource development prospects. The total plant cost (including the cost of an 84-meagwatt-electric combined cycle power plant) estimated by Choi and others (1997) is $415 million. This is in contrast to capital requirement per plant of $2 - 4 billion for a typical liquid natural gas (LNG) facility. Thus the investment hurdle is far less for a once-through F-T liquids plus power plant than for an LNG plant. Moreover, the proven gas reserves required per site for an F-T plant amounts to only 1 exajoule, relative to 6 - 8 exajoules for an LNG facility.

Thus F-T technology makes it feasible to exploit much smaller remote gas fields than is feasible for LNG. Of course, this strategy requires that there be markets for the electricity coproduct, and many remote gas fields are not near transmission networks. However, the costs of building transmission lines to deliver baseload electricity to demand centres might often be economically attractive (requiring much less investment than for energy-equivalent gas infrastructure) given the low generation cost, particularly if outputs of several small fields in the region could be combined for long-distance transmission at scales on the order of 1 gigawatt-electric.

Air Products is also developing liquid-phase reactor technology for DME production (Peng and others, 1997; Peng and others, 1998). As in the case of MeOH and F-T liquids production, liquid-phase reactor technology used in conjunction with once-through process is expected to make DME production from natural gas economically attractive at relatively small scales.

There needs to be continuing research and development on all these liquid-phase reactor synthetic fuels technologies - especially on DME, which has attractive attributes but is the least developed of the technologies described here. But the main barriers to the deployment of these technologies are institutional rather than technological: Their economic viability depends on the ability of the polygenerator to sell the electricity coproduct into the electricity grid at a fair market price. Reforms to promote more competition in power markets will be helpful in nurturing the development of syngas-based synthetic fuels technology.

Hydrogen and the quest for near-zero emissions. The strategic importance of having an energy system for the long term in which H_2 is a major clean energy carrier has been noted (see box 8.1). No CO_2 or air pollutants are emitted during use when H_2 is consumed in fuel cells. If H_2 is burned in gas-turbine-based power plants, the only air pollutant is NO_x (formed by oxidation of N_2 in air); but these NO_x emissions can be controlled to very low levels by lean combustion strategies or by injecting steam or water into the combustor or compressor air stream of suitably designed power plants.[41]

When H_2 is made electrolytically by decomposing water from renewable or nuclear electric sources, CO_2 and pollutant emissions associated with H_2 manufacture and thus life-cycle CO_2 emissions are also zero or near zero. When H_2 is made from a fossil fuel, life-cycle pollutant emissions are also very low,[42] although CO_2 emissions from H_2

manufacture can be high. However, for large, centralised H_2 production facilities, CO_2 can be generated as a nearly pure by-product that can be disposed of (for example, in a geological reservoir) at modest cost. Even if this CO_2 had to be disposed of in aquifers (where there is no credit for enhanced resource recovery) that are as far away as 500 kilometres from production sites, the cost of disposal based on current technology would be less than $50 a tonne of carbon (Williams, 1999b). If the H_2 so produced were a competitive energy carrier (which is not the case today), the cost of CO_2 emissions avoided would approach this disposal cost - which is less than the least avoided cost for the coal electric generation technologies described in table 8.9.

Concerns are often raised about H_2 safety. In this regard, H_2 is better than other fuels in some ways, worse in other ways, and in still other ways just different (Ringland, 1994). However, H_2 can be used safely if procedures are followed that respect its physical and chemical properties (box 8.3). Such theoretical considerations are buttressed by extensive experience with residential town gas (typically 50 percent H_2), which was widely used in the United States until the 1940s and in Europe until the 1960s, and is still used in China and South Africa.

The manufacture of H_2 from a fossil fuel begins with syngas production - the mostly costly step in the overall process. Thus, if the world pursues the syngas-based energy technologies described in previous sections, it would be embarked on a path that would facilitate a transition to H_2.

The dominant commercial H_2 production technology is reforming of natural gas. H_2 can also be made through gasification of any carbonaceous feedstock (Williams and others, 1995), including coal, heavy oils, biomass, or municipal solid waste (Larson, Worrell, and Chen, 1996), or through electrolysis of water using renewables (for example, hydropower,

wind, or solar; Ogden and Williams, 1989), nuclear energy, or other power sources. Until fossil fuel prices are far higher than at present, electrolytic approaches for producing H_2, now and in the future, will tend to be much more costly than making H_2 from natural gas, coal, or other fossil fuels - even when the added costs of CO_2 sequestration are taken into account (Williams, 1998; IPCC, 1996a).[43]

Technology for producing H_2 from fossil fuels is well established commercially. Although H_2 is currently used only in niche applications as an energy carrier (for example, for the U.S. National Aeronautics and Space Administration's space shuttle launches), it is widely used in oil refining and the chemical process industries. H_2 is produced commercially in the United States at a rate of 8.5 million tonnes a year (Moore and Raman, 1998) or 1.2 exajoules a year (1.25 percent of U.S. energy consumption). Several large-scale polygeneration plants have been or are being built around the world for the coproduction of H_2 and electricity from petroleum residues through gasification (see table 8.6).

Such projects reflect the rapid growth (10 percent a year) in demand for H_2 at refineries, as a result of cleaner transportation fuel mandates and requirements for processing heavier crudes. The major obstacle to widespread deployment of H_2 as an energy carrier is the fact that H_2 is not competitive in energy markets. There are two ways this situation might change: the emergence of H_2-using technologies that put a high market value on H_2, and H_2 production technologies that reduce its cost - the prospects for which are reviewed in the next two sub-sections.

Enhancing the prospects for H_2 with fuel cell vehicle technology. Successful commercialisation of fuel cell vehicles would give H_2 a high market price, because H_2 fuel cell vehicles would typically be much more fuel efficient that internal combustion engine

vehicles with the same performance and would offer substantial air quality benefits.[44] Although H_2 storage onboard vehicles is challenging, problems seem to be surmountable with existing technologies, and some promising advanced options could plausibly make H_2 storage no more challenging for fuel cell vehicles than gasoline storage is today for internal combustion engine vehicles (box 8.4).

BOX 8.3. HYDROGEN SAFETY

Hydrogen is widely perceived to be an unsafe fuel, because it burns or detonates over a wider range of mixture with air than other fuels, and very little energy is required to ignite H_2 mixed with the minimum amount of air needed to completely burn it. Although H_2 is flammable in air over a wide range of mixtures, when used in unconfined spaces (as will be typical in transport applications), the lower limits for flammability and detonability matter most. In this regard, H_2 is comparable to or better than gasoline. Gasoline and natural gas can also be easily ignited with low-energy ignition sources such as electrostatic discharges - like those that result from a person walking across a rug. Moreover, in dilute mixtures with air, the ignition energy for H_2 is essentially the same as for methane. In another regard, H_2 has an advantage over gasoline: In case of a leak in an unconfined space, H_2 will disperse quickly in the air because of its buoyancy, whereas gasoline will puddle.

An important safety issue for H_2 is leaks - prevention, detection, and management, particularly in confined spaces. Areas where H_2 is stored and dispensed have to be well ventilated; because of H_2's buoyancy, this means providing vents at the highest points in ceilings. Considering all these issues, a major study of H_2 safety (Ringland, 1994) concluded that "H_2 can be handled safely, if its unique properties - sometimes better, sometimes worse, and sometimes just different from other fuels - are respected."

BOX 8.4. HYDROGEN STORAGE FOR MOTOR VEHICLES

Storing H_2 onboard motor vehicles is challenging because of H_2’s low volumetric energy density. With current technology, the least costly option is compressed gas (typically at 350 atmospheres; James and others, 1996), for which the storage density is less than one-tenth gasoline’s.

Volumetric storage densities do not have to equal that of gasoline to make H_2 storage manageable - in part because of the high fuel economies of fuel cell vehicles. An H_2 fuel cell car that meets the PNGV fuel economy goal (2.94 litres per 100 kilometres or 80 miles a gallon, gasoline-equivalent) would require 240 litres of compressed H_2 storage capacity for a 680-kilometre (425-mile) range between refuellings, compared to 64 litres for a typical gasoline ICE car (9.4 litres per 100 kilometres, or 25 miles a gallon fuel economy). A prototype H_2 fuel cell van introduced in 1997 by Daimler Benz involved storing H_2 cylinders in an under-the-roof compartment; a car with a PNGV fuel economy and a 680-kilometre range might use three such cylinders, each 110 centimetres long and 32 centimetres in diameter.

In comparison with gaseous storage, storage volumes could be reduced by half with metal hydrides, but storage system weight would increase several times, and costs would be much higher. H_2 liquefaction could reduce storage volumes to a third of those for compressed H_2 but would require consuming electricity equivalent to a third of the H_2 (higher heating value basis), and boil-off (typically 1.5 - 2 percent a day) makes this option wasteful for private cars that are typically used an hour a day or less.

H_2 storage using carbon nanofibres is under development through alternative approaches (Chambers and others, 1998; Chen and others, 1999; Liu and others, 1999; Dresselhaus, Williams, and Ecklund, 1999). It offers the potential for dramatically improving performance - some options are even able to store H_2 at relatively high energy densities near atmospheric pressure and ambient temperatures. Successful development of one or more of these technologies might make storing H_2 in fuel cell vehicles no more difficult than storing gasoline in gasoline internal combustion engine cars.

A fierce global competition is under way to accelerate the development of fuel cell vehicles (Steinbugler and Williams, 1998; Appleby, 1999). Nearly all major auto manufacturers have produced test vehicles (table 8.14). Several automakers have set goals to introduce fuel cells into the automotive market during 2003 - 10. Developmental efforts are focused on PEM fuel cells. Industrial interest is motivated largely by the prospect that fuel cell vehicles will have zero or near-zero emissions, without tailpipe emission controls. The air quality benefits provide a powerful rationale for developing fuel cells for a wide range of vehicles, including buses, trucks, locomotives, and small two-and three-wheeled vehicles (which account for much of the air pollution in cities of the developing world; PCAST Panel on ICERD[3], 1999), as well as cars - the focus of fuel cell vehicle development in industrialised countries.

Under a zero-emission-vehicle (ZEV) technology-forcing policy to meet its air quality goals, the state of California has mandated that 10 percent of new cars sold in the state be ZEVs by 2003. Initially, the battery-powered electric vehicle (BPEV) was the focus of efforts to meet the mandate. Although there have been some significant advances (for example, in electric drive-train technology), the BPEV is no longer the only focus of ZEV developmental efforts; the technological challenges of overcoming the problems of long battery recharging times, modest vehicle ranges between rechargings, and high costs have proven formidable. The ZEV mandate has also been catalytic in stimulating industrial interest in fuel cell vehicles as an alternative technology that offers good prospects for addressing the shortcomings of the BPEV.

Although the natural fuel for fuel cell vehicles is H_2, many efforts aimed at

commercialising fuel cell vehicles are emphasising H_2 production onboard the car from either MeOH or gasoline, because an H_2 refuelling infrastructure is not yet in place. MeOH and gasoline are liquid fuels that are easily stored and transported. Processing MeOH onboard cars is easier and has been successfully demonstrated. Processing gasoline is more difficult, requiring higher temperatures, but gasoline offers the clear advantage that no new fuel infrastructure is needed. Detailed modelling has shown that MeOH and gasoline fuel cell vehicles would be a third less fuel efficient than H_2 fuel cell vehicles but still more fuel efficient than gasoline-fuelled internal combustion engine vehicles (Ogden, Kreutz, and Steinbugler, 1998).

Although fuel cell vehicles might be launched on the market using MeOH or gasoline, an H_2 fuel cell vehicle would be less costly to own and operate - largely because of expected lower capital and maintenance requirements. Even if fuel cell vehicles are launched with gasoline or MeOH, an internal market pressure subsequently would develop that would encourage a shift to H_2 as soon as an H_2 infrastructure could be put in place (Steinbugler and Williams, 1998; Ogden, Kreutz, and Steinbugler, 1998). By the time fuel cell vehicles account for a large enough fraction of the market to justify the infrastructure investments, a plausible scenario for supplying the needed H_2 would be to establish near each major city one or more large facilities for making H_2 from some mix of natural gas, refinery residues, coal, municipal solid waste, and biomass. These facilities should be large enough to justify economically sequestration of the separated CO_2 but sufficiently close to vehicle refuelling stations that only relatively modest-scale H_2 pipeline networks would be needed to distribute the H_2 to users (Williams, 1999b).

With such an infrastructure in place, fuel cell vehicles could then offer transportation services with zero or near-zero emissions of CO_2 (as well as air pollutants). The added cost to consumers for sequestering the separated CO_2 would amount to less than $0.002

per kilometre of driving (less than 1 percent of the cost of owning and operating a car), assuming current H_2 production technology for coal and natural gas (Kaarstad and Audus, 1997) and fuel cell vehicles having the target gasoline-equivalent fuel economy for the U.S. PNGV (80 mpg, or 2.94 litres per 100 kilometres).

The potential for reducing CO_2 emissions with H_2 fuel cell vehicles depends on how fast the technology penetrates the market. Even the most optimistic scenarios project capturing a fourth of the new car market by 2025 - which implies displacing only a tenth of all cars by that time. If all fuel cell cars were fuelled with H_2, and the separated CO_2 were sequestered, global CO_2 emissions would be only 0.1 GtC less than under business-as-usual conditions. Such considerations illustrate the long periods required for new technologies to have major impacts - and underscore the importance of launching accelerated development initiatives for technologies that offer major public benefits, so that they can have significant impacts 25 years in the future.

Can fuel cell vehicles compete? The leading North American developer of PEM fuel cell fuels has said in press releases that PEM fuel cells will be competitive in transport applications when production volumes reach 250,000 - 300,000 fuel cell vehicle engines a year, which the company expects well before 2010. Some studies in the public domain also project that mass-produced fuel cell vehicles can be competitive (Thomas and others, 1998a, b). Although the economics of fuel cell vehicle technology are still very uncertain, no intrinsic costs of PEM fuel cell materials or fabrication are so obviously high as to preclude mass-produced fuel cell vehicles from being competitive. The fuel cell’s inherent simplicity (for example, no moving parts) and mild operating conditions (80 degrees Celsius) relative to internal combustion engine vehicles also suggest substantial cost reduction opportunities.

It will not be easy for the fuel cell vehicle to displace the internal combustion engine

vehicle, an entrenched, mature technology. Moreover, as noted, internal combustion engine technology is still being improved. Japanese automakers have already introduced clean spark-ignited internal combustion - electric hybrids that offer twice the fuel economy of conventional internal combustion engine vehicles. It will be difficult for gasoline fuel cell vehicles to compete with these hybrids, because the two sets of vehicles will have comparable efficiencies, and it is always difficult for a new technology to displace an old one - unless it offers enormous advantages.

The air pollution issue will be centre stage during the competition between fuel cell and hybrid internal combustion engine vehicles to be car of the future. Meeting air quality goals will be especially challenging for hybrids involving compression-ignition engines (NRG, 1998). Moreover, Ross and others (1995) estimate that there will be a growing gap between actual life-cycle emissions and regulated emissions for internal combustion engine vehicles with spark-ignited engines (see table 8.3).

Hybrids fueled with H_2 would pose significant competition for H_2 fuel cell vehicles in the race to zero emissions. NO_x would be the only significant pollutant emission for H_2 hybrids; because ultra-lean combustion is feasible with H_2 fueling, NO_x emissions of hybrids can be controlled to low levels. However, such hybrids would be less fuel efficient than H_2 fuel cell vehicles and thus more costlyto operate. The economic winner of this race to zero emissions depends on what relative vehicle costs turn out to be when vehicles are mass produced.

TABLE 8.14. FUEL CELL TEST VEHICLES AROUND THE WORLD

Year	Company	Fuel storage	Fuel cell power system			Range (kilometres)
			Power output	Auxiliary	Vehicle	

			(kilowatts)	power	type	
1993	Ballard	Pressurised H_2	120	No	Bus	160
1994	DaimlerChrysler	Pressurised H_2	54 net	No	Necar I (van)	130
1996	DaimlerChrysler	Pressurised H_2	50 net	No	Necar II (van)	250
1996	Toyota	Metal hydride	20	Pb battery	Car	250
1997	Ballard	Pressurised H_2	205 net	No	Bus	400
1997	DaimlerChrysler	MeOH (onboard reformer)	50	No	Necar III (car)	Greater than 400
1997	Mazda	Metal hydride	20	Ultra-capacitor	Car	170
1997	DaimlerChrysler	Pressurised H_2	190 net	No	Nebus (bus)	250
1998	Renault	Liquid H_2	30	Ni-MH battery	Station wagon	400
1998	Opel	MeOH (onboard reformer)	50 (motor)	Ni-MH battery	Minivan	-
1999	DaimlerChrysler	Liquid H_2	70	No	Necar IV (car)	400
1999	Ford	Pressurised H_2	75	No	Car	96
1999	Nissan	MeOH (onboard reformer)	10	Li-ion battery	Station wagon	-
1999	Honda	Metal hydride	60	Ni-MH	Car	-

				battery		
1999	Honda	MeOH (onboard reformer)	60	Ni-MH battery	Station wagon	-
2000	General Motors	Chemical hydride	75	Ni-MH battery	Car	800

Source: Various fuel cell vehicle newsletters.

Despite the many uncertainties, there is growing private sector confidence in the prospects for making fuel cell vehicle technology competitive, as indicated by substantial auto industry investment levels and growing attention being paid to the technology also by the oil industry (API, 1999).[45] Making fuel cell vehicles competitive in the near term requires accelerated commercialisation, because current costs are high, and large production volumes are needed to bring costs down quickly. (Fuel cells - like many other new technologies - are expected to be well described by learning curves for which costs decline 10 - 30 percent for each cumulative doubling of production; Rogner, 1998; Lipman and Sperling, 1999.) Recognising this, one industrial consortium for fuel cell vehicle development - automakers DaimlerChrysler, Ford, and Mazda, and fuel cell developer Ballard Power Systems - has bullishly set an ambitious goal of selling 40,000 fuel cell cars a year by 2004.

Enhancing prospects for hydrogen with advanced hydrogen production technologies. H_2 might eventually be able to compete in fuel cell vehicle markets using current H_2 production technologies. But new H_2 production technologies are needed to enable H_2 to compete in applications such as stationary power generation, for which H_2 fuels cells do not offer major efficiency advantages over conventional fossil energy technologies. There are many opportunities.

One set of opportunities involves integrating CO_2 removal into production processes in creative ways - for example, coproduction of H_2 and F-T liquids from natural gas to reduce costs by avoiding the need for a costly air separation plant.[46] Advanced gas separation technologies warrant focussed attention, especially for separating CO_2 and H_2.47 One innovative technology receiving development support from the U.S. Department of Energy involves cooling the pressurised gaseous mixture (mainly CO_2 and H_2) exiting the water-gas shift reactors to less than 10 degrees Celsius, then bubbling the gases through a water column. Under appropriate conditions the H_2 passes through but the CO_2 is converted into a CO_2 clathrate hydrate that is heavier than water and easily removed. With this technology it might be possible to substantially reduce the energy and capital costs of CO_2 removal and disposal (Spenser, 1999; Spencer and Tam, 1999).

Another promising set of options involves using inorganic membrane reactors to simultaneously drive the water-gas shift reaction towards maximum H_2 yield and separate the H_2 and CO_2. Williams (1999b) points out that using such reactors offers the potential for making H_2 from coal (without CO_2 sequestration) at costs that approach typical natural gas prices for electricity producers in the United States, with CO_2 sequestration costs adding $1.00 - 1.50 a gigajoule. At such costs, coal-derived H_2 with sequestration of the separated CO_2 could be an economically attractive option even for central-station power generation in a greenhouse gas emissions-constrained world.

In one variant of this concept, the Parsons Group has proposed a plant design to make H_2 from coal that involves separating H_2 from CO_2 at high temperatures using porous ceramic membranes. Substantial cost reductions are projected relative to conventional methods for making H_2 from coal (Parsons Infrastructure and Technology Group, 1998;

Badin and others, 1999). But Williams (1999b) suggests that attention be given instead to carrying out the gas separations at much lower temperatures than proposed by the Parsons Group, to avoid the formidable technological difficulties of high-temperature processes. Operation of membrane reactors at lower temperatures increases the number of technological options for gas separation, including especially promising non-porous composite metal membrane technologies that can provide H_2 of high purity - important for applications involving PEM fuel cells, which are poisoned by CO at low (10 parts per million by volume) concentrations.

If methane hydrates could be exploited at large scales (chapter 5), ways would eventually be needed to extract the energy without releasing the separated CO_2 into the atmosphere, to prevent a greenhouse disaster.[48] One way this might be accomplished is to make H_2 from the methane using steam reforming and leave behind in nearby reservoirs the by-product CO_2 as CO_2 clathrate hydrates (PCAST Energy Research and Development Panel, 1997), which are stable under pressure and temperature conditions similar to those for methane hydrates. Indeed, sub-seabed disposal of CO_2 in the form of clathrate hydrates has been proposed as a major option for effectively disposing of CO_2 generated in fossil energy systems (Koide and others, 1997).

Alternatively, H_2 could be extracted through methane thermal decomposition to produce H_2 and carbon black (Steinberg and Cheng, 1989), an endothermic process. If some of the produced H_2 is burned to provide the needed heat, the process would be CO_2-emissions free, and the net H_2 energy yield would still be more than 50 percent of the energy content of the original methane. Although this conversion would have much less than the 80 - 85 percent efficiency that can be achieved with conventional reforming technologies, methane thermal decomposition might prove interesting if there are unforeseen obstacles

(political or technical) to large-scale CO_2 sequestration (carbon black is easier to store than CO_2).

Other near-term advanced fossil energy technologies

Besides the advanced technologies described above that are consistent with all sustainable development goals, other near-term advanced fossil energy technologies - for both power generation and synthetic fuels production - offer improved performance relative to today’s technologies but would not be consistent with all sustainable development goals. In particular, they would not provide a good basis for moving over the longer term towards near-zero pollutant and CO_2 emissions. Yet some of them might become important in limited applications.

Power generation

Other candidate advanced coal-based power-generating technologies include ultrasupercritical coal steam-electric plants, IGCC plants that employ air-blown gasifiers, and pressurised fluidised-bed combustion (PFBC).

Ultrasupercritical coal steam-electric plants. A typical modern coal steam-electric plant with flue gas desulphurisation has 35.5 percent efficiency (see table 8.4), a level that has changed little since the 1950s. Attention has recently been given to opportunities to achieve higher efficiencies by using advanced alloys that make it possible to increase peak steam temperatures and pressures to ultrasupercritical steam conditions and by deploying efficiency-boosting cycle configurations (for example, double reheating, which increases efficiency by increasing the average temperature at which heat is added to the cycle). For example, ELSAM of Denmark has built a 400-megawatt-electric ultrasupercritical, coal steam-electric plant with an announced efficiency of 47 percent (Kjaer, 1993).[49] This project should be watched closely to see if operators can avoid the high forced outage

rates that plagued earlier attempts to operate steam-electric plants under ultrasupercritical conditions. Increased forced outage risk will be more important under future competitive market conditions than in the past, when most electric companies had a guaranteed rate of return on investment.

One limitation of the technology is that it is not nearly as well suited as the IGCC for cogeneration. The low electricity-heat output ratio characteristic of steam cycles using back-pressure turbines (see figure 8.1) limits the overall cost reduction potential, as well as the overall power-generating and fuel-saving potentials from cogeneration based on this technology (compare tables 8.7 and 8.8). In addition, the cogeneration operating mode is typically not cost-effective for systems that involve steam reheating.[50]

Achieving ultra-low air pollutant emissions will be much harder than for IGCC plants with O_2-blown gasifiers, because contaminants to be removed are in flue gas volumes 40 - 60 times larger than for the pressurised fuel gases from which pollutants are removed in IGCC plants. In addition, although ultrasupercritical steam plants release a fifth less CO_2 per kilowatt-hour than conventional steam-electric plants, achieving deep reductions in CO_2 emissions requires approaches that involve removing CO_2 from flue gases, which is much more costly than for IGCC plants with fuel gas decarbonisation equipment (see table 8.9).

Coal IGCC technology based on air-blown gasification. Although commercial coal IGCC technology is based on O_2-blown gasifiers, the research and development community is interested in developing systems based on air-blown gasifiers - motivated largely by a desire to eliminate the air separation plant.[51] Interest in air-blown gasification in turn has driven interest in research and development on warm gas clean-up technologies that could reduce the thermal losses from cooling down the gas exiting the gasifier for clean-up and heating it up again for combustion.[52]

Government support for innovation is needed - particularly for long-term research, and for early deployment of new technologies.

Development of warm gas clean-up is proving to be difficult.[53] But even if these difficulties were eventually overcome, broadly based comparisons of O_2- and air-blown gasifier-based systems (Simbeck, 1995) show that O_2-blown gasifiers are usually preferred for coal.[54] The advantage of avoiding the need for O_2 is offset by disadvantages of air-blown gasifier systems, considering only direct costs. First, because of the lower heating value of the gas, an air-blown gasifier requires twice the gasifier volume as does an O_2-blown gasifier - important in light of the capital intensity of gasifiers. Second, for gasifiers operated at comparable temperatures, the sensible heat of the raw gas leaving an air-blown unit is typically 50 - 60 percent more than for an O_2-blown gasifier, which implies a significant increase in the duty of the raw gas cooler - one of a gasification plant's more costly items.

In addition, seven strategic considerations amplify the relative benefits of O_2-blown systems. First, O_2-blown gasification facilitates an evolutionary strategy in which gas turbines and combined cycles are fired first with natural gas and converted later to coal as natural gas prices rise - a difficult option for air-blown gasifiers without major system modifications and technical risk. Second, air-blown units are less able to exploit advances in gas turbine technology that enable higher turbine inlet temperatures and higher efficiencies.[55] Third, with air-blown gasification, polygeneration strategies (see above) other than cogeneration of process heat and electricity are not practical. Fourth, warm-gas

clean-up is essential for favourable system economics with air-blown gasifiers, but merely an option that offers higher efficiency for systems with O_2-blown gasifiers - the benefit of which must be traded off against capital cost, reliability, and environmental considerations. Fifth, if warm-gas clean-up can be made commercially viable, environmental benefits would be less for air-blown systems, because dilution of the contaminants with N_2 makes achieving the same levels of air pollutant emissions reduction more costly than for O_2-blown systems. Sixth, achieving deep reductions in CO_2 emissions with IGCCs equipped with air-blown gasifiers would require flue gas CO_2 recovery approaches that are much more costly than are fuel gas recovery approaches for O_2-blown systems (see table 8.9). Seventh, successful development of air-blown gasifier-based systems would not make a major contribution in moving towards near-zero emissions in the long term, while the O_2-blown gasifier is the key near-term technology that would enable this evolutionary strategy.

Pressurised fluidised-bed combustion. PFBC is an advanced technology evolved from atmospheric pressure fluidised-bed combustion (AFBC) technology, which is already on the market (with both bubbling- and circulating-bed variants).[56]

A review of AFBC technology is helpful in understanding PFBC. Although not more energy-efficient than pulverised coal plants, AFBC plants make it possible to use a wide range of coals and other fuels in a single combustor. One manifestation of this fuel flexibility is the ability to cofire coal units with biomass, a common practice in Scandinavia (Saviharju, 1995). This practice makes it possible both to realise the economies of larger-scale conversion for biomass than are typically feasible with dedicated biomass units and to reduce the AFBC unit's air pollutant and greenhouse gas emissions (as a result of the typically low sulphur and nitrogen contents of biomass feedstocks and their CO_2 emissions neutrality). (This flexibility to accommodate biomass is also provided by

fluidised-bed gasification technologies.)

At the low operating temperatures of AFBC plants, thermal NO_x emissions are considerably less than for pulverised coal plants, although about 10 percent of nitrogen in coal can be converted to NO_x (Pillai, 1989). For some coals and in areas with tight regulations on emissions, NO_x control equipment is needed. Up to 90 percent sulphur removal can be accomplished by adding limestone or dolomite to the bed; higher removal rates are theoretically possible but impractical because of the large quantities of limestone and dolomite needed and consequent high solid waste disposal rates. AFBC sulphur removal technology is practically restricted to use with relatively low-sulphur coals and for meeting regulatory requirements calling for relatively modest sulphur removal. The high pH of the waste (because of free lime, accounting for a third of limestone-related wastes) might cause the waste to be classified as hazardous in some areas and thus be subject to especially stringent disposal regulations. Moreover, waste utilisation strategies are difficult because potentially useful products (such as gypsum) are intimately mixed with other wastes.

When a fluidised-bed combustor is pressurised to 10 - 15 atmospheres, electricity can be produced by feeding the combustion-product gases to a gas turbine after clean-up and using the turbine exhaust gases to produce steam in a heat recovery boiler that drives a steam turbine. Such PFBC technology thus makes higher efficiency possible with a combined cycle, while reducing boiler size. Early PFBC units have 37 - 40 percent efficiencies. Improved designs, such as ABB Carbon’s design with an ultrasupercritical double-reheating PFBC boiler and steam turbine, can achieve 43 percent efficiency.

PFBC and IGCC based on O_2-blown gasifiers are the leading competing advanced coal power technologies. The main PFBC advantages are fuel flexibility (as for AFBC) and simplicity - because PFBC uses one reactor (combustor) relative to two (gasifier and

combustor) for IGCC - which might give PFBC a near-term cost advantage. A major PFBC limitation is that, unlike the IGCC, it cannot take advantage of continuing advances in gas turbine technology, because the turbine inlet temperature is fixed at the bed temperature, which is far below the state of the art for modern gas turbines. Future systems might be able to exploit gas turbine technology advances,[57] although they would not be simpler than IGCC systems and thus would lose the original appeal of the PFBC concept and current designs. Efficiencies of 45 - 48 percent are being targeted. As in the case of air-blown IGCC technology, successful development of warm gas clean-up technology is key to achieving high performance with future PFBC systems. Like AFBC, PFBC is limited mainly to use with low-sulphur coals, because of solid waste disposal issues; PFBC typically generates more solid waste per unit of fuel consumed than AFBC.

Energy research and development is cheap insurance for addressing the climate change challenge.

The higher efficiencies offered by PFBC can lead to reduced CO_2 emissions - for example, a 43 percent efficient unit equipped with an ultrasupercritical double-reheat PFBC boiler and steam turbine would have a fifth less CO_2 emissions than a typical new 35.5 percent efficient pulverised coal plant. But achieving deep reductions in CO_2 emissions would require approaches that involve removing CO_2 from flue gases, which are more costly than for IGCC plants with fuel gas decarbonisation equipment (see table 8.9). In addition, unlike most combustion systems, greenhouse gas emissions from fluidised-bed combustion units can be significantly greater than emissions from fuel carbon. A powerful additional greenhouse gas is nitrous oxide (N_2O), which is produced efficiently from

nitrogen in coal at the low operating temperatures of fluidised beds.[58]

Measurements of N_2O in AFBC exhaust gases (de Soete, 1993) correspond to a 5 - 25 percent increase in CO_2-equivalent greenhouse gas emissions relative to CO_2 emissions from coal burning. Sub-bituminous coals and lignite generally produce less N_2O than bituminous coals, and circulating fluidised beds tend to produce more N_2O than bubbling beds, possibly because of the longer residence times for the former (de Soete, 1993). Reducing N_2O emissions from AFBC units will be technologically challenging. For PFBC systems, N_2O emission data are relatively scant. Measurements at the Swedish Vrtan PFBC cogeneration plant (Dahl, 1993) show that emissions vary markedly with operating conditions. From these measurements, it is estimated that when NO_x control technologies are not deployed, the CO_2-equivalent emissions of N_2O emissions are 3 - 10 percent of CO_2 emissions from coal burning. In addition, when NH_3 injection is used for NO_x control, the CO_2-equivalent emissions are 5 - 18 percent of CO_2 emissions from coal burning.

Although it is a significant improvement over conventional pulverised coal and AFBC technologies, PFBC technology is limited for the longer term by constraints similar to those for ultrasupercritical pulverised coal steam plants and IGCCs using air-blown gasifiers. For applications involving cogeneration of process heat and electricity, characteristic PFBC electricity-heat output ratios are much less than those for IGCC technologies (because of the relatively minor role played by the gas turbine in PFBC units), so that cogeneration economics would tend to be less favourable than for IGCC systems. And, as for conventional ultrasupercritical pulverised coal steam-electric plants, energy-efficient PFBC designs that employ steam reheat cycles are generally poor candidates for cogeneration. Moreover, PFBC systems cannot exploit the syngas-based polygeneration opportunities feasible with O_2-blown gasification.

Whether PFBC can meet its long-term goals depends critically on success with warm-gas cleanup; comments relating to warm-gas clean-up for PFBC versus IGCC with O_2-blown gasifiers would be similar to those presented above for warm-gas clean-up for IGCC with air-blown gasifiers versus IGCC with O_2-blown gasifiers. Perhaps the most fundamental shortcoming of PFBC technology is that, as for ultrasupercritical steam technology and IGCC technology with air-blown gasifiers, it is not a stepping stone along the path to near-zero emissions for coal.

Liquid fuels production through direct liquefaction of low-quality feedstocks

An alternative to the indirect liquefaction technology that provides syngas-derived synthetic fuels from carbonaceous feedstocks (see above) is direct coal liquefaction, which involves adding H_2 to coal in a solvent slurry at elevated temperatures and pressures. Direct liquefaction was commercialised in Germany and Japan to provide liquid fuels during World War II, when coal-derived gasoline levels reached 75,000 barrels a day (Simbeck, Dickenson, and Moll, 1981). Interest in the technology virtually disappeared when low-cost Middle Eastern oil became available in the 1950s but was revived during the oil crises of the 1970s, when several pilot and demonstration projects were carried out. Interest almost disappeared again with the collapse of the world oil price in the mid-1980s. Today the technology is again being considered as an option for making synthetic fuels in natural-gas-poor regions such as China.[59]

An advantage often claimed for direct liquefaction is that overall conversion efficiencies are higher than for indirect liquefaction (Stiegel, 1994). However, to the extent that potential efficiency gains relative to indirect liquefaction can be realised, this is largely due to the fact that direct liquefaction plants produce liquids that are aromatic-rich and thus require less H_2 than typical fuels derived through indirect processes (Simbeck, Dickenson, and Moll, 1981). But here an improvement in efficiency would represent a step

backwards for environmental management, because new environmental regulations aim to propel a shift to inherently cleaner fuels - for example, recent U.S. regulations limit aromatic contents of transport fuels.

A review of direct coal liquefaction technology by a panel convened by U.S. President Bill Clinton to advise him on energy research and development needs (PCAST Energy Research and Development Panel, 1997) found that the technology:

- **Offered no advantages relative to indirect liquefaction.**
- **Would lead to liquid fuels that generate twice as much CO_2 as petroleum-based fuels.**
- **Would provide no obvious path to achieving deep reductions in CO_2 emissions over the long term at low cost - in contrast to syn-gas-based strategies, which can evolve to the point where H_2 is a major energy carrier with low-cost sequestration of the separated CO_2.**

Because of such considerations, the panel recommended that the U.S. Department of Energy terminate federal research and development funding for direct coal liquefaction. The panel also recommended that the freed-up resources be used to support research and development on syngas-based technologies that are consistent with a technological evolution over the longer term to near-zero emissions for fossil fuels.

The arguments set forth here favouring indirect over direct liquefaction apply to other low-quality feedstocks as well as coal - for example, tar sands and heavy crudes, which are far more abundant than conventional oil and natural gas resources (chapter 5). Such feedstocks could be used to produce cleaner fuels through indirect liquefaction, and ultimately H_2 with sequestration of the separated CO_2, thereby helping to realise the long-

term goal of near-zero emissions for fossil fuels.

Conclusion

The fossil energy system can evolve in ways consistent with sustainable development objectives if public policies guide a high rate of innovation toward super-clean fossil energy technologies. On the basis of present knowledge, it is possible to identify and describe advanced fossil energy technologiesthat meet sustainable development objectives at reasonable cost.

The trend towards the growing use of natural gas is making clean energy more widely available at attractive prices. But the move to gas in the context of an increasingly competitive energy industry is also making innovation difficult. To stimulate the needed innovation, policy-makers could set long-term goals for advanced fossil energy technologies, including near-zero emissions of both air pollutants and greenhouse gases. They could also enact policies with incentives to motivate the private sector to develop and deploy technologies that would lead the fossil energy system towards a future consistent with sustainable development objectives.

Key technologies needed to bring about such a fossil energy future are advanced gas turbines, fuel cells, advanced syngas production technologies, and inorganic membranes for gaseous separations. The private sector is fully capable of carrying out most of the needed research and development for all such technologies. But government support for innovation is needed - particularly for long-term research, for which private sector incentives are especially weak, and for early deployment of new technologies that offer major public benefits related to sustainable development (PCAST Panel on ICERD[3], 1999).

Major roles for developing countries (where most fossil energy demand growth will take place) in the innovation process are also needed to ensure that innovations are tailored to

developing country needs (PCAST Panel on ICERD[3], 1999). Government also could play a role in guiding and facilitating new infrastructure development - for example, for natural gas delivery systems in the near term and H_2 delivery systems in the long term. Both the energy innovation process and infrastructure-building activities have strong international dimensions and highlight the importance of fostering international collaborations - for example, through industrial joint ventures (PCAST Panel on ICERD[3], 1999).

Reforms that encourage competitive power markets could help put industry on a path to fossil energy with near-zero emissions by helping launch syngas-based polygeneration activities that provide clean synthetic fuels for transportation, cooking, and other applications, along with electricity and process steam.

Two sets of research and development issues stand out for a long-term fossil energy strategy. One concerns the effectiveness, safety, and capacity for CO_2 disposal. A better scientific and technical understanding of these issues, on a region-by-region basis, would help policy-makers decide how much climate-change mitigation resources to commit to this strategy relative to other options, such as renewable or nuclear energy. The other concerns the prospects for energy recovery from methane hydrates. A better scientific and technical understanding of this resource, on a region-by-region basis, would help policy-makers decide how to allocate resources for long-term fossil energy research and development (for example, how to allocate between coal and methane hydrate options). Getting answers to both sets of questions would require expenditures of public resources, because private sector interest is weak as a result of the long-term nature of the questions. But in both cases, the required expenditures are likely to be modest.

An uncertainty regarding the strategy outlined here - guiding the fossil energy system towards widespread fuel decarbonisation with CO_2 sequestration - is whether the public will find large-scale sequestration acceptable. The public has to be convinced that

sequestration will be safe and effective. Broad public participation in activities related to decarbonisation and sequestration should be encouraged - for example, a wide range of stakeholder groups should have roles in reviewing scientific studies, demonstration projects, and planning activities. The fact that the least costly technologies for CO_2 disposal also offer near-zero emissions of air pollutants should help gain public confidence. The public will want to know the trade-offs, in relative costs and side effects, among fossil, renewable, and nuclear options for realising the goal of near-zero emissions, and also the trade-offs between pursuing near-zero emissions and not doing so.

Advanced nuclear energy technologies

Nuclear power dominates electricity production in several countries[60] and is making substantial contributions to global energy: At the 1998 level of installed nuclear capacity of 349 gigawatts-electric, nuclear power provided 16 percent of world-wide electricity (IAEA, 1999). Although there is likely to be modest expansion until 2010, most projections are that the nuclear share of electricity generation will be less in 2020 than today. And many projections envisage that nuclear power's absolute contribution in electricity will be no more than today and might even be less.[61]

The regional outlook has more contrasts.[62] For industrialised countries, which accounted for 81 percent of nuclear generating capacity in 1997, the U.S. Energy Information Administration (EIA) projects that nuclear capacity in 2020 will be 44, 75, and 100 percent of the capacity in 1997 for its low-growth, reference, and high-growth scenarios. The projected reductions in capacity in industrialised countries reflect the expectation that nuclear plants retired at the ends of their useful lives will not be replaced, although utilities in several countries are considering plant life extensions. For Eastern Europe and the countries of the former Soviet Union (which accounted for 13 percent of global nuclear capacity in 1997), the EIA projects that, for these same scenarios, capacity in 2020 will be

26 gigawatts-electric less, 6 less, and 24 more than in 1997. For developing countries (which accounted for 6 percent of global nuclear capacity in 1997), the EIA projects capacity increases for the respective scenarios of 10, 34, and 67 gigawatts-electric, with most of the expansion in Asia.

There is a nuclear power stalemate in many regions, in part because the technology is much more costly than was originally projected - a problem exacerbated by low fossil fuel prices, growing numbers of new competing technologies, and increasingly competitive market conditions world-wide in the electric power industry. In addition, the prospects for continuing and expanding the contribution of nuclear power to the world energy supply have been clouded by concerns related to safety, radioactive waste management, and nuclear weapons proliferation and diversion. All these issues have led to a loss of public confidence in nuclear technology.

Rationale for reconsidering the nuclear option

If ways can be found to make nuclear power widely acceptable, it could help address problems posed by conventional fossil energy technologies - especially health impacts of air pollution and climate change arising from CO_2 build-up in the atmosphere. Considering the chain of activities for nuclear power production (including mining operations, nuclear fuel conversion, nuclear power plant operation, decommissioning, transportation, and waste disposal), recent analysis carried out under the European Commission's ExternE Program estimated that the total cost of environmental damage (local, regional, and global impacts integrated during a period of up to 100,000 years) is about $0.003 per kilowatt-hour when evaluating future impacts with a zero discount rate (Rabl and Spadaro, 2000).[63] This is far less than the environmental damage costs of coal steam-electric plants with the best available control technologies, but (considering the margin of error in these estimates) is comparable to damage costs of modern natural gas combined cycle and coal IGCC plants (see table 8.1).

These externality cost comparisons for nuclear and fossil energy systems are incomplete, however. The calculations do not take into account costs associated with the potential diversion of nuclear materials to weapons purposes or wars triggered by concerns about access to energy or water supplies, which are inherently difficult to quantify in economic terms. For nuclear power, greenhouse gas emissions are zero, a benefit (also inherently difficult to quantify) that must also be taken into account in comparing nuclear and fossil energy technologies.

As an aid in thinking about potential roles for nuclear energy in mitigating climate change, consider two alternative scenarios:

- **A high-growth scenario that extrapolates the EIA's high-growth scenario to 2100, with nuclear capacity increasing to 1,000 gigawatts-electric by 2050, 3,000 by 2075, and 6,500 by 2100.[64]**
- **A low-growth scenario that extrapolates the EIA's low growth scenario to zero nuclear capacity by 2050.**

The greenhouse gas mitigation benefit of the high-growth relative to the low-growth scenario would be reductions in CO_2 emissions of 225 GtC during the next 100 years if coal power were displaced and 110 GtC if natural gas power were displaced[65] - reductions equivalent to 16 percent and 8 percent of emissions during the period under a business-as-usual future.[66] This calculation shows that, for nuclear energy to make a significant contribution to coping with climate change, nuclear capacity must be increased by at least an order of magnitude during the next 100 years.

The need for advanced technologies

It is desirable to see if acceptable solutions can be found to the economic, safety,

proliferation and diversion, and waste management concerns that presently constrain the prospects for further nuclear deployment.[67] Solutions are desirable both because nuclear energy can potentially contribute to solving the major problems posed by conventional fossil energy technologies and because of uncertainties associated with the prospects of other advanced energy-supply options (both the advanced fossil technologies described above and the renewable technologies described in chapter 7). Emphasis here is on technological strategies and the kinds of research and development that offer promise in making the nuclear option more attractive. However, socio-political considerations are also discussed.

The sociopolitical context

Identification of promising technologies for future nuclear power is complicated by the lack of consensus in the broader community of stakeholders (utilities, governments, publics, scientists, engineers) on goals for nuclear energy innovation and ways to address the goals. At the root of these difficulties is the fact that the issues cannot be resolved in narrow technical and economic terms. Perceptions of costs, safety, proliferation and diversion impacts, and risks in waste management matter as much as engineers' calculations.

To illustrate, consider that although most experts believe waste disposal is the least challenging problem facing nuclear energy and is soluble, many in the general public regard waste disposal the most daunting challenge. Public concerns about managing wastes for the very long term thus have focused attention in the technical community on waste mitigation strategies that could radically shorten the time required to keep waste under surveillance (for example, nuclear waste separation and transmutation proposals) - relatively costly strategies that some experts believe would exacerbate proliferation and diversion concerns without gaining many benefits. As long as there are such seemingly fundamental disagreements, nuclear energy innovation efforts will remain unfocused.

Most projections are that the nuclear share of electricity generation will be less in 2020 than today.

The analysis of technologies and strategies that follows is based largely on technical considerations. But the reader should bear in mind that bringing about a ‘nuclear renaissance’ would require more than just doing the right research and development. Because - after an ambitious start - nuclear power has lost its lustre, the barriers to its revival are probably higher than if the technology were entirely new. Nuclear power may never again be seen as "a welcome sign that the modern age is dawning; it can at best hope to be tolerated. Therefore, nuclear power must have a substantial advantage if it is to be used" (Lidsky, 1991). And new nuclear technology must appeal not only to experts but also to the public.

Nuclear electricity costs

Nuclear fuel costs are low relative to fossil fuel costs. For example, in 1998 the average fuel cost for nuclear power in the United States was $0.0054 per kilowatt-hour (Ryan, 1999) - a third that for coal steam-electric power and a fourth that for natural gas combined cycles in Europe (see table 8.4). But operation and maintenance costs and capital costs have been high for nuclear plants. Operation and maintenance costs have been declining somewhat in recent years as a result of competitive pressures but are high relative to operation and maintenance costs for fossil fuel plants. For example, in 1998 operation and maintenance costs for U.S. nuclear plants averaged $0.014 per kilowatt-hour (Ryan, 1999) - more than three times the operation and maintenance cost for U.S. coal or natural gas plants (see table 8.4). Operation and maintenance costs have been high for nuclear plants largely because of the large operating staff - typically 800 - 900 for

a large 1,100-megawatt-electric power station. Staffing requirements are high, to a large degree because of the need to operate the plants within current regulatory guidelines designed to ensure safety.

A recent survey of electricity generation costs in 18 countries found that installed capital costs for new nuclear power plants around the world are $1,700 - 3,100 per kilowatt-electric (Paffenbarger and Bertel, 1998),[68] much higher than for typical new fossil energy plants. Despite such high capital costs, the study found that, for new plants, nuclear power would be less costly than coal- or natural-gas-based power in two countries - China and France.

The costs of alternatives to nuclear power are fast-moving targets in many regions. Privatisation is taking place in many countries where the power sector was once dominated by parastatal energy companies, and the trend is towards more competition in power markets, where competitive new smaller-scale technologies have ended the historical natural monopoly status of electricity generation. As noted, the natural gas combined cycle has become the technology of choice for thermal power generation where natural gas is readily available. Where competitive conditions are strong, costs have been coming down, even for mature technologies such as pulverised coal steam-electric plants - for example, by a fourth in the United States from 1992 - 95 (Stoll and Todd, 1996).

Moreover, since the early 1980s the average price of coal for electric companies in the United States has fallen by a factor of 2 in real (inflation-adjusted) terms, and the average coal price is expected to fall a further 30 percent by 2020, to $0.90 a gigajoule (EIA, 1999a). In Europe fossil energy prices are not as low as in the United States, but even there prices have been falling; from 1983 - 95 the average prices for coal and natural gas imported into the European Union fell from 55 to 65 percent (Decker, 1999). Such intensifying competition from fossil fuels can be expected to spread to more and more regions undergoing electric industry restructuring.

Quantification of the external costs of today's fossil energy plants would improve the economics of nuclear power. But these benefits will not be so great with various advanced fossil energy technologies: Fossil energy technologies now coming onto the market can provide electricity with very low emissions of local and regional air pollutants. Moreover, as discussed above, even the climate change benefits offered by nuclear power likely will face stiff competition from advanced coal systems that involve fuel decarbonisation and CO_2 sequestration. Thus direct economic costs will continue to be important in determining the future of nuclear power. If nuclear power is to become economically viable once again, innovations will be needed that can provide electricity at costs competitive with other future near-zero-emission energy technologies. Moreover, this has to be done in ways that are consistent with meeting concerns about nuclear safety, proliferation and diversion, and radioactive waste disposal.

Nuclear safety

If substantial quantities of the radionuclides produced in nuclear reactors are released to the environment, the result can be considerable damage - not just the direct impacts on people and the environment but also the indirect impacts on the viability of the industry itself. The loss-of-coolant accident at Three Mile Island shook investor confidence in nuclear power, even though radioactive material releases to the environment were minimal. As a result of the Chernobyl accident, the public has little confidence that nuclear power is safe.

> For nuclear energy to qualify as a sustainable energy option, concerns regarding safety, waste disposal, and proliferation must be addressed in ways that enable it to compete on an economic basis.

Unlike Chernobyl-type reactors, the light water reactors (LWRs) that dominate nuclear power around the world have had a remarkably good safety record. But LWR accidents can happen. The Three Mile Island accident stimulated numerous improvements in reactor safety. Detailed calculations indicate that, for current U.S. reactors, the probability of core damage is less than 10^{-4} per reactor per year, and the probability of significant radioactive releases is a tenth as large (Fetter, 1999). But this record has been achieved at a high cost for a complex technology to minimise serious accident risk, and the technology is unforgiving of error.[69]

Advanced reactors are likely to be significantly safer. Two approaches to safety are used in advanced reactor designs. One is aimed at improving the technology in an evolutionary manner with the present defence-in-depth approach to safety, which provides redundancy or multiple levels of active interventions by equipment and operators to prevent fuel damage - and, even if fuel is damaged, to prevent the release of significant quantities of radioactivity to the environment. Although enough redundancy can reduce the probability of failure to arbitrarily small values, sceptics can always claim that not all events leading to accidents can be imagined, so that the probabilities used in probabilistic risk assessment are not accurate (Spiewak and Weinberg, 1985). Such systems depend on proper operation and maintenance of reactors, which cannot always be assured.[70]

The complexity of active safety systems also can tempt workers to ignore regulations they believe to be overly conservative (as was the case at Chernobyl). And finally, complex systems can make it difficult to achieve the goal of reducing capital and operation and maintenance costs. An alternative approach to safety is to identify and develop technologies that offer a high inherent degree of safety without the need for complicated, capital-intensive safety controls - often called passive safety systems. If passive systems can be developed and made to work effectively, they offer the potential to address safety and cost challenges simultaneously. Lidsky (1991) argues that new reactor technologies

have to be not only safe but demonstrably safe, because "the public has lost faith in all experts and has little trust in probabilistic risk assessments".

Nuclear proliferation and diversion

The knowledge needed to design and fabricate fission bombs is available to almost every nation. For many years, lack of access to nuclear explosive materials,[71] not lack of knowledge, has been the main technical barrier to the spread of nuclear weapons capability. The essence of the potential nuclear weapons link to fission power (box 8.5) is that this technology provides the possibility of obtaining this missing ingredient, in the form of either uranium-enrichment capability or plutonium extractable from spent reactor fuel through chemical reprocessing. Access to such materials makes it easier for additional countries to acquire nuclear weapons (Holdren, 1989). In the future, as sub-national criminal groups become more sophisticated, the related threat that these too might acquire nuclear bombs or radiological weapons by misusing nuclear energy technologies may grow in importance (Willrich and Taylor, 1974; Leventhal and Alexander, 1987; LLNL, 1998).

Are proliferation and diversion resistant technologies needed? A multifaceted effort is required to minimise the motivations for proliferation: control commerce in sensitive facilities, equipment, and materials; detect any misuse of such facilities or equipment or diversion of materials; and intervene where necessary to prevent an errant nation or sub-national criminal group from acquiring nuclear weapons. The main approach to addressing these challenges has been the Nuclear Non-Proliferation Treaty and associated international safeguards and nuclear supplier agreements (box 8.6). These deterrents are more significant than ever before: A nation-state deciding to launch a nuclear weapons programme today would need to find motivation sufficient to offset the penalties of discovery, the possibilities that the enterprise might not succeed, and costs that might be prohibitive.

The issue of how to deal in the future with the risk that nuclear materials in civilian nuclear power programmes will be used for weapons purposes is a focus of debate. One view is that this risk can be adequately addressed by a system of institutional controls, building on the historical success of the Nuclear Non-Proliferation Treaty (Walker, 1999). Others argue that if the role of nuclear energy were to expand substantially (for example, to the extent that nuclear power could have a significant role in mitigating climate change risks), the requirements imposed on institutional measures such as safeguards would increase significantly. Thus, it is argued, research and development is needed to see if the inherent resistance of nuclear energy systems to proliferation can be increased, thereby lessening the intensity of reliance on institutional measures alone to reduce proliferation risks (Bunn, 1999; Feiveson, 1999; Williams and Feiveson, 1990; PCAST Energy Research and Development Panel, 1997; PCAST Panel on ICERD^3, 1999).[72]

Clearly, additional countries can acquire nuclear weapons if they want them badly enough to openly abrogate the Nuclear NonProliferation Treaty or to take their chances that a clandestine weapons programme will not be detected. And such countries can do this whether or not civilian nuclear energy technology is available to them as a partial basis for their weapons effort. It appears that the steps taken to strengthen the non-proliferation regime in recent years have significantly increased the difficulty, cost, and detectability of such efforts to produce nuclear weapons.

Looking to the future, the key proliferation and diversion issue is how to minimise the temptations and advantages that nuclear programmes may offer potential proliferator states and sub-national groups - that is, how to minimise any contribution of nuclear energy to the rate at which additional states or groups seek to acquire and succeed in acquiring nuclear weapons.

The sections below explore the prospects for reducing proliferation and diversion risks with advanced technologies, which could be especially important in a world where nuclear

power is developed on a scale far larger than at present.[73] Two approaches to proliferation and diversion resistance are considered. One involves systems in which plutonium and other weapons-usable materials are never separated from spent fuel, the radioactivity of which deters proliferation and diversion efforts. These systems build on the fact that contemporary light-water reactors using low-enriched uranium in a once-through fuel cycle that leaves the plutonium mixed with fission products in spent fuel are the most prominent operational example of a relatively proliferation-and-diversion-resistant fuel cycle. An improved variant of this approach is advanced once-through reactor and fuel cycle technologies for which the quantities of weapons-usable materials available in spent fuel are reduced - thereby reducing incentives to mine spent fuel for weapons-usable materials. A completely different approach is to convert nuclear energy to electricity and hydrogen in large international energy parks at which weapons-usable materials are maintained under tight international control and to distribute these carriers to distant consumers. The next subsection discusses proliferation and diversion issues associated with nuclear fuel reprocessing and plutonium recycling for today's civilian nuclear power technology.

BOX 8.5. NUCLEAR WEAPONS PROLIFERATION RISKS POSED BY NUCLEAR ENERGY TECHNOLOGIES

Nuclear explosives can be made both from highly enriched uranium and plutonium, including plutonium produced in civilian nuclear power plants. Although there are complications in weapon design, fabrication, and maintenance when reactor-grade instead of weapons-grade plutonium is used, these do not add substantially to those that must be faced when using any nuclear-explosive material for making weapons, according to individuals and groups with authoritative knowledge of nuclear weapons technology (Holdren, 1989; Mark, 1993; CISAC, 1994, 1995). Reactor-grade plutonium can be used to construct devastating nuclear weapons at all levels of technical sophistication (DOE, 1997). So that the dangers of reactor-grade plutonium will not continue to be misunderstood, in recent years the U.S. Department of Energy (custodian of the world’s most sophisticated knowledge base on the subject) has made this point clear in unclassified reports and has allowed those with DOE nuclear-weapon security clearances to make explicit statements about it in other forums. Especially relevant points are made in the following quotations:

> The difficulties of developing an effective design of the most straight forward type are not appreciably greater with reactor-grade plutonium than those that have to be met for the use of weapons-grade plutonium. (Mark, 1993)
>
> Using reactor-grade rather than weapons-grade plutonium would present some complications. But even with relatively simple designs such as that used in the Nagasaki weapon - which are within the capabilities of many nations and possibly some subnational groups - nuclear explosives could be constructed that would be assured of having yields of at least 1 to 2 kilotons. With more sophisticated designs, reactor-grade plutonium could be used for weapons having considerably higher minimum yields. (CISAC, 1994)
>
> At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapons-grade plutonium. (DOE, 1997)

Although there are more direct ways for a country to acquire nuclear bombs than from its commercial nuclear energy facilities (for example, centrifuges for uranium enrichment and special reactors dedicated to plutonium production), the acquisition of nuclear explosive materials is made easier if the requisite technical skills and infrastructure are already in place through a nuclear power programme. The existence or prospect of commercial nuclear power in a country, moreover, provides a legitimating cover for nuclear activities that, without electricity generation as their manifest purpose, would be considered unambiguously weapons-oriented and thus potentially subject both to internal dissent and external sanctions and counter-measures. Feiveson (1978) points out that even countries that initially have no intention of acquiring nuclear weapons might later be more likely to acquire them, under altered internal or external political circumstances, because their having a nuclear power programme has made it easier to do so.

BOX 8.6. INSTITUTIONAL MECHANISMS ADDRESSING PROLIFERATION RISKS OF NUCLEAR ENERGY

International efforts to stem the spread of nuclear weapon capabilities have been more successful than almost anyone at the beginning of the nuclear era dared to hope. Rather than the dozens of nuclear weapon states once predicted, today only eight states are believed to have nuclear weapons capabilities, a number that has not increased for more than 10 years. Indeed, South Africa has provided the first case of genuine nuclear disarmament - a state that had full control over its own arsenal of nuclear weapons and agreed to give them up entirely. The international regime that has achieved this result includes both political elements designed to convince states that acquiring nuclear weapons is not in their interest, and technical elements designed to increase the detectability, difficulty, and cost of nuclear weapons acquisition. The foundation of this regime is the Nuclear Non-Proliferation Treaty, which now has 187 parties - more than the United Nations Charter. The civilian nuclear energy programmes of all of these besides the five nuclear-weapon states recognised by the treaty are subject to ‘full scope’ IAEA (International Atomic Energy Agency) safeguards designed to verify their commitments not to acquire nuclear weapons.

Several parts of the non-proliferation regime are designed to address the nuclear weapons proliferation risks posed by civilian nuclear energy programmes. The most fundamental part is IAEA safeguards, which allow international verification of the peaceful use of all nuclear materials in non-nuclear-weapons states (OTA, 1995). In the aftermath of the post - Gulf War revelation of Iraq’s large-scale clandestine nuclear weapons programme, and the failure of previous IAEA monitoring and inspections to detect it, IAEA safeguards are being substantially strengthened, with new measures designed not only to verify that nuclear material at declared sites is not misused, but also to help ferret out activities that may be taking place at secret sites (Hooper 1997). Other critically important institutional measures to reduce the risk of proliferation include the international system of controls on exports of technologies that could be used for nuclear weapons programmes, as well as programmes to ensure that all potentially weapons-usable nuclear material is secure and accounted for - and so cannot be stolen for use in nuclear weapons by proliferating states or terrorist groups.

But confidence in the future effectiveness of the non-proliferation regime in general, and the barriers to use of nuclear-energy technologies for proliferation in particular, cannot be unconditional or complete. The non-proliferation regime itself is imperilled by the recent efforts in this direction by Iraq and the Democratic People’s Republic of Korea, and by the failure of the recognised nuclear-weapons states (above all, Russia and the United States) to move more decisively, in the aftermath of the cold war, towards fulfilling their legal obligation under Article VI of the Nuclear Non-Proliferation Treaty to negotiate in good faith towards nuclear disarmament (Barletta and Sands, 1999). The extensively documented case of Iraq, in particular, demonstrates that eternal vigilance is required to prevent states from clandestinely acquiring critical technologies despite the existence of export controls on them.

Moreover, the safeguards implemented by the IAEA - which include monitoring of records and on-site inspections at reactors and fuel-cycle facilities, along with the broader measures beginning to be implemented in the aftermath of the Gulf War - at best only provide assurance that diversion of nuclear materials to weaponry will be detected. These safeguards are not intended to prevent such diversion, or to prevent theft of these materials by sub-national groups. (Protection against theft is the province of individual states; there are no binding international standards governing the adequacy of such protection, and levels of protection vary world-wide from excellent to grossly inadequate.) Even detection of diversion or theft is not completely assured, both because of limitations on the resources being provided to the IAEA and because of the intrinsic difficulty of the task of safeguarding nuclear materials, particularly when large quantities of weapons-usable nuclear material are being processed in bulk.

This difficulty has been recognised since the dawn of the nuclear era. Addressing the adequacy of international inspections for the purpose of preventing nuclear proliferation, the Acheson-Lillienthal Report that formed the basis of the Baruch Plan for international control of nuclear weapons (submitted to the UN by the United States in 1946) stated that "there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled only by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are not merely technical but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations, each free to develop atomic energy but only pledged not to use bombs...So long as intrinsically dangerous activities may be carried on by nations, rivalries are inevitable and fears are engendered that place so great a pressure on a systems of international enforcement by police methods that no degree of ingenuity or technical competence could possibly cope with them" (Lillienthal and others, 1946).

Nuclear fuel reprocessing and plutonium recycling. Several countries have begun commercial-scale reprocessing to recover plutonium along with unused uranium from spent fuel (with intentions to dispose of the separated radioactive wastes in geologic repositories at a future date) and to recycle plutonium in mixed-oxide uranium-plutonium (MOX) fuel for LWRs. These activities make the nuclear weapons proliferation risk a more serious concern than when LWRs fuelled with low-enriched uranium are operated on once-through fuel cycles.

Commercial LWR fuel-reprocessing systems have been established in France (at La Hague), Russia (Chelyabinsk-Ozersk), and the United Kingdom (Windscale-Sellafield).[74] These facilities are nodes of a global nuclear fuel management system in which spent fuel is sent from reactors to reprocessing plants, and the separated constituents (uranium, plutonium, radioactive wastes) are to be returned (eventually) to the fuel owners.[75] These three sites are reprocessing fuel from about 150 reactors operating in nine countries (Berkhout, 1998).

Reprocessing facilities now handle a fourth of the spent fuel discharged from power reactors. The rest is in interim storage, either targeted for eventual geological disposal in canisters designed for direct disposal without reprocessing, or (for the majority of the material outside Canada and the United States) pending a decision on whether to go to geological storage or reprocessing. Today 20 tonnes of plutonium is being separated from spent fuel annually world-wide; by the end of 1995, 180 tonnes had been separated from civilian nuclear reactor spent fuel - 18 percent of the total plutonium discharged from these reactors (Albright, Berkhout, and Walker, 1997). Some of the recovered plutonium and uranium mixed with fresh uranium (MOX fuel) is being used as fuel for LWRs. The challenge of managing the growing stockpile of separated civilian plutonium (the total quantity separated less the amount used as fuel in plutonium recycling, about 180 tonnes world-wide as of 2000) parallels the problem of managing the growing quantity of separated surplus military plutonium produced by dismantling excess nuclear weapons in the aftermath of the cold war, now approaching 100 tonnes in Russia and the United States combined (PCAST Panel on ICERD[3], 1999).

Although it reduces uranium requirements for power generation, the reprocessing-recycling option does not compete in economic terms with once-through use of low-enriched uranium fuel in LWRs,[76] reflecting the fact that it has become clear that the world has large, low-cost reserves of uranium (chapter 5). Yet reprocessing and recycling activities continue for a number of reasons: sunk capital costs, government subsidies, long-term contracts signed when uranium seemed scarcer and costlier, reluctance to throw away the energy content of unrecycled plutonium and uranium, perceptions that reprocessed wastes are easier to manage than spent fuel, and lack of alternatives to reprocessing as a means of removing spent fuel from reactor sites in the short term (PCAST Panel on ICERD[3], 1999).

Nuclear waste disposal

The radioactive by-products of fission must be isolated from the human environment to the extent that they can never return in concentrations that could cause significant harm. Spent fuel removed from a reactor is first stored for at least a few years in cooling pools at the reactor site. After the very short-lived fission products have decayed, the fuel can:

- **Remain in the pools (if they have sufficient capacity).**
- **Be stored on-site in dry casks (which provide a safe and economic alternative for storage for several decades).**
- **Be transported to an away-from-reactor storage site (either pools or dry casks).**
- **Be transported to a reprocessing plant or a geologic disposal facility.**

In many cases efforts to expand long-term storage capacity on-site or particularly to establish large away-from-reactor stores not associated with reprocessing or disposal sites have encountered public opposition, leaving some utilities in doubt as to where to put their spent fuel as their cooling ponds fill up.

Eventually, the spent fuel will either be reprocessed, and the high-level wastes sent to a long-term storage site, or it will be encapsulated in suitable canisters and sent directly to a long-term disposal site. Safe ways of storing wastes for periods up to 1 million years may be required. For the first hundred years of the required isolation period, the radioactivity and heat of these wastes are dominated by fission products. After several hundred years, the major concerns are the very-long-lived transuranics (various isotopes of plutonium, neptunium, and Americium) and long-lived iodine and technetium fission products.

There is a consensus among states using nuclear energy that deep geologic disposal in mined repositories is the best currently available approach for disposal of nuclear

wastes.[77] And most experts believe that geologic repositories can be designed to be safe (NEA, 1999). However, to date, no country has yet disposed of any spent fuel or high-level waste in such a repository.

Because wastes are concentrated, disposal cost is not a significant issue. In the United States, for example, utilities are charged only $0.001 per kilowatt-hour for management and disposal of their spent fuel (2 - 3 percent of generation cost). Detailed calculations suggest that this will be fully adequate to finance that portion of the cost of the nuclear waste disposal programme attributable to civilian spent fuel (DOE, 1998). Costs would be higher for small countries if repositories were established there to accommodate only their own wastes.

Public and political opposition to waste disposal has delayed efforts to open targeted repositories in some countries. There have also been technical problems. But long-term waste disposal should not be an intractable problem from a technical perspective. Even if some wastes eventually leak from repositories, problems would be manageable because of the small storage space required.

For example, storage density limits for spent LWR fuel at Yucca Mountain, Nevada, are 41 square metres per megawatt-electric of nuclear generating capacity for a power plant operated for 30 years (Kadak, 1999). At this storage density, the area required for storing all radioactive waste generated during the 21st century for the global high-nuclear-growth scenario above is 270 square kilometres. Suppose that a waste-isolation land area 10 times as large is purchased at a cost of $100,000 per hectare to be maintained in perpetuity with no human intrusion. The required land area is 0.003 percent of the continental land areas. The cost of the land would be $0.0009 per kilowatt-hour generated (2 percent of generation cost) for a 10 percent discount rate, or $0.00002 per kilowatt-hour (0.05 percent of generation cost) for a 0 percent discount rate, assuming in both cases that the land is paid for in 2000.

Because the areas required are modest, it is not necessary for every country to develop its own repository. Globally, only a small number of sites is needed. Restricting storage to a small number of favourable sites around the world would be attractive for various reasons (McCombie, 1999a, b; McCombie and others, 1999; Miller and others, 1999), including realisation of scale economies, the potential for optimising the prospects for achieving demonstrable safety, and various additional reasons discussed below.

Although coping with the radioactive waste problem seems manageable from a technical perspective, a technical fix by itself is not a solution: A real solution has many non-technical features as well (see below).

Must spent fuel be reprocessed for radioactive waste disposal? At one time, it was thought by some that reprocessing is needed to safely dispose of radioactive wastes. However, the International Fuel Cycle Evaluation, carried out from 1977 - 79 to consider the commercial use of plutonium, concluded that spent fuel itself could be safely disposed of in a waste repository (STATS, 1996). This conclusion has been strengthened by subsequent intensive investigations of spent fuel disposal in several countries (for example, Finland, Sweden, and the United States).

Nevertheless, both public opposition to interim away-from-reactor storage sites and delays in opening long-term waste repositories are causing great difficulties for utilities, because storage pools at reactor sites are fast approaching capacity. In some countries (not the United States, which has abandoned civilian reactor fuel repossessing), nuclear utilities have been forced into reprocessing as a de facto interim waste management strategy. But reprocessing does not solve the waste disposal problem - it merely buys time and transforms the spent fuel management problem into several other problems associated with plutonium disposition: management of high-, medium-, and low-level wastes at reprocessing plants; management of transuranic wastes at plutonium fuel fabrication plants; and, eventually, decommissioning wastes from these plants (plus

residual spent-fuel disposal, if plutonium is not recycled indefinitely).

Should long-lived wastes be separated and transmuted? The challenge of storing the very-long-lived components of radioactive wastes has led to various separations and transmutation (S&T) proposals for separating out the hazardous, long-lived components and transmuting them by neutron bombardment to form nuclides that would be either stable or radioactive with much shorter half-lives. The Committee on Separations Technology and Transmutation Systems (STATS) was formed by the U.S. National Research Council at the request of the U.S. Department of Energy to evaluate alternative S&T options for addressing such issues and assess their implications for nuclear waste management.

The STATS committee investigated several alternative reactor and particle accelerator systems. It found that, although S&T might be technically feasible for some of the options studied, the need for permanent long-term storage would remain. Many decades to centuries would be required to reduce the radioactivity to the low levels specified by S&T proponents as their objective, and disposal costs would increase substantially (STATS, 1996).[78] Moreover, it is unlikely that the modest reduction in waste-disposal risk for the long term (which is already very small) would outweigh the high costs and increased near-term accident and proliferation risks that would be associated with S&T (Fetter, 1999). The most active programmes in this area are those of France, Japan, Russia, Sweden, and the United States.

Towards geological disposal. As noted, the focus world-wide for long-term disposal is on geologic repositories. All concepts rely on multiple barriers provided by the storage canisters, the backfill material used to surround the canisters in the storage rock, and the rock itself. Test results suggest that corrosion-resistant containers may be able to keep nearly all the waste contained for thousands of years.

Effectively addressing nuclear concerns probably requires advanced technologies as well as improved institutional risk management strategies.

There have been setbacks, though not always for scientific and technical reasons; public and political opposition has sometimes slowed technical progress. In the United States, public acceptability considerations led Congress to choose the Yucca Mountain site in sparsely populated Nevada, even though technically it may not be an especially good site (Fetter, 1999).[79]

Advances in waste disposal science and technology have been rapid in Sweden, where the decision to phase out nuclear power facilitated a societal consensus on a waste disposal programme (Gillena, 1994). Swedish researchers are developing a scheme to put spent fuel in copper-clad steel canisters to be embedded in bentonite clay in a granite monolith 600 metres underground at a site near the sea; they anticipate a million-year canister lifetime for the site’s reducing conditions (Whipple, 1996). Should the storage canisters eventually leak, surrounding backfill material and rock would inhibit movement of leaked wastes to the surface.

The widely shared judgement of the technical community that long-term storage can be made safe is based on careful assessments of safety and environmental impacts that take into account both waste characteristics and the properties of all barriers involved. Several extensive safety assessments have been carried out in OECD countries. Potential radiation exposures have been calculated to be close to zero for periods of 100,000 years for all scenarios and sites considered; for longer periods, the risks are so small as to impose very small additional externality costs, even if there is no discounting for these uncertain

remote future events.[80]

Technical uncertainties need further study.[81] But none is likely to be a show-stopper. Moreover, there is time to resolve technical issues because, from a technical perspective, there is no urgency to move wastes from interim to permanent long-term storage sites. In fact, delay for a period of 50 years would not only buy time to improve scientific understanding of long-term storage issues and storage technology, but would also facilitate waste disposal by reducing required heat removal rates as a result of radioactive decay of fission products. Delaying long-term waste disposal would probably require establishing secure storage sites (which might be the same as the long-term disposal sites) for spent fuel for part of this cooling off period; but, as recent experience has shown, this will not be easily accomplished in the political arena.

Will spent fuel repositories become plutonium mines? A final technical waste disposal issue relates to the concern that, if radioactive wastes are stored as spent fuel rather than reprocessed wastes, repositories might one day be mined as sources of low-cost plutonium for nuclear weapons. The Committee on International Security and Arms Control of the U.S. National Academy of Sciences has identified general proliferation hazards associated with spent fuel management, including the issue of mining waste repositories for plutonium recovery, as an area warranting continued research "at the conceptual level" (CISAC, 1994).

Peterson (1996) has argued that, after a hundred years or so, the costs of clandestine tunnelling into spent fuel repositories to recover plutonium would be less than the costs for conventional dedicated facilities to acquire plutonium. In examining this issue, Lyman and Feiveson (1998) found that the range of conditions under which repository mining would look attractive relative to other means of acquiring plutonium is narrow. Although safeguards would be needed in perpetuity, the measures needed to deter mining need not involve expensive and intrusive inspections but could focus on containment and

surveillance procedures, including remote monitoring by satellites. And the safeguard management challenge would be greatly facilitated if there were only a small number of repositories around the world.

Perspective on radioactive waste disposal. The most important unresolved issues relating to radioactive waste disposal are political rather than technical. Providing adequate disposal capacity for nuclear wastes has been and is likely to continue to be fraught with political controversy.

The world would be better off if secure, internationally managed, interim, away-from-reactor storage sites could be set up for spent fuel, even for periods of 50 years before activating any permanent repository. If such interim storage capacity were to become available, fewer and fewer utilities would be willing to pay the extra near-term costs of reprocessing, and the reprocessing industry would slowly be competed out of business. Yet the world is not moving in this direction. As noted by Hckel (1997):

> **The historical record of the past decades is littered with the acronyms of defunct proposals for an internationalised back end fuel cycle... Not only have these not materialised; it appears that at the back end of the fuel cycle internationalisation is actually on the retreat... Stalemate and procrastination seem to be a general phenomenon of fuel cycle policy everywhere.**

O’Neill (1998) identifies several factors as inhibiting the development of an international spent fuel management regime or regimes: widespread political and public opposition to siting of storage facilities (which would be heightened in a country faced with the prospect of becoming the world’s nuclear dumping ground) and to transport radioactive substances within countries and across borders; differences in national interests and practices (for example, it is unlikely that most states with existing reprocessing capacity will give it up); sovereignty concerns; compliance, information gathering, and

dissemination issues (states need assurances that if they comply, others will too, with appropriate verification provisions); and the long time horizons involved (for example, even interim storage sites would have to outlast not only political lives but the actual lifetimes of most political leaders).

O'Neill offers no easy answers to this stalemate but suggests an evolutionary strategy focussing initially on regional rather than global arrangements, because states in a geographic region are more likely to share common norms (although, of course, animosities can also be intense at the regional level). And although both interim and permanent disposal face political opposition, there are probably fewer obstacles to the former.

Advanced nuclear generating options for the immediate future

In what follows, near-term advanced nuclear generating technology options are described, focussing on advanced LWR and fuel cycle technologies, and the pebble bed modular reactor. No attempt is made to be comprehensive; rather, the intent is to use these examples to illustrate what advanced technologies offer to address the challenges posed by current nuclear technologies.

Advanced light water reactors

Can LWR technology improvements help in addressing the challenges facing current technologies? Simpler plant designs and shorter plant construction periods would help bring down costs. Improved safety designs could help restore public confidence in nuclear power. And more proliferation-resistant designs would reduce proliferation and diversion risks.

Evolutionary advanced light water reactors. In recent years the main nuclear reactor vendors have developed modified LWRs that offer both improved safety and lower cost

than LWRs now in use (NRC, 1992; CISAC, 1995; Kupitz and Cleveland, 1999).[82] These modified LWRs build on more than 40 years of experience with LWR technology to provide technological improvements in standardised designs, for which there can be a high degree of confidence that performance and cost targets will be met. All of the modified LWRs use active but simplified safety systems, and some have some passive safety features.

One reactor in this category is the Westinghouse AP600, a 600-megawatt-electric pressurised water reactor (PWR). The design is simpler than existing PWRs; and it is modular, with about half the capacity of most existing PWRs - which allows some components to be factory-built and assembled faster on-site at lower cost than for plants that are entirely field-constructed. The AP600 is expected to be safer than existing PWRs, able to be constructed in 3 years, and cost about 15 percent less than existing PWRs of the same capacity (NPDP, 1998). In late 1999 the AP600 received design certification from the U.S. Nuclear Regulation Commission.

Also in this category are the ABB/Combustion Engineering System 80+ and the GE Advanced Boiling Water Reactor (ABWR); both received design certification from the U.S. Nuclear Regulatory Commission in 1997. The System 80+ is a large (1,350-megawatt-electric) unit, for which the estimated core damage frequency is 2.7 times 10^{-6}, two orders of magnitude lower than for its predecessor. The ABWR has as a design objective a core damage frequency of less than 10^{-6} and a target capital cost that is 20 percent less than for BWRs previously built in Japan (NPDP, 1998). Two ABWRs are now operating in Japan. Two more are under construction in Japan and also in Taiwan (China).

In Europe a Framatome-Siemens joint venture and a group of 'nuclear' German utilities have developed the European pressurised water reactor (EPR), a 1,750-megawatt-electric system designed to specifications endorsed by utilities in Europe - with hoped-for economies of scale at this large unit size. The EPR is being offered on the international

market.

Shifting light water reactors to a denatured uranium-thorium fuel cycle. If the advanced LWRs described above were operated on low-enriched uranium in once-through fuel cycles, they would be as proliferation and diversion resistant as existing LWRs, with fission products in spent fuel deterring plutonium removal by would-be proliferators and diverters. But because plutonium inventories build up quickly (200 kilograms a gigawatt-electric per year) - posing a significant proliferation hazard if the plutonium is separated by reprocessing, and conceivably making spent fuel at reactors or in off-site storage potential targets for proliferation and diversion - attention has been given recently to LWRs operated on a denatured uranium-thorium once-through fuel cycle that is more proliferation-diversion-resistant even than current LWRs operated on a once-through fuel cycle (Gasperin, Reichert, and Radkowsky, 1997; Herring and MacDonald, 1998).

Although it would not differ markedly from current LWR technology with regard to capital cost and safety, the LWR operated on a denatured uranium-thorium once-through fuel cycle would produce less transuranic wastes than current LWRs. Most important, it would have proliferation and diversion resistant features relating to both plutonium and uranium. Only a fifth as much plutonium would be generated in spent fuel as in an LWR fuelled with low-enriched uranium. Moreover, the plutonium would contain a significant amount of Pu-238, which generates heat that makes weapon manufacture more difficult. In this cycle the U-233 is bred from thorium denatured by the U-238, at enrichment levels such that this uranium cannot be used to make weapons without further enrichment; moreover, the uranium contains gamma-emitting daughters of U-232, which makes weapon manufacture more difficult.[83]

The technology is not diversion-proof. Reliable nuclear weapons could be made by many nations from both plutonium and uranium that could be recovered from spent fuel by relatively straightforward chemical means.[84] In the hands of terrorists or an

unsophisticated country, the recovered plutonium could be used to make weapons with yields of 1 or 2 kilotons. These reservations notwithstanding, this system would be more proliferation-resistant than a conventional LWR operated on slightly enriched uranium, because incentives for recovering weapons-usable material from spent fuel would be less.

Yet discussion of the specifics of this particular technology shows that setting goals for proliferation and diversion resistance will not be easily accomplished. This is because trade-offs must be taken into account in considering the weapons potential of the plutonium and uranium materials involved.

> There seem to be reasonably good prospects for making reactors demonstrably safe while simultaneously reducing costs.

The pebble bed modular reactor. For decades, a different approach to nuclear fission based on moderating the reactor with graphite and cooling it with helium (rather than using water for both purposes in LWRs) has been under development in several countries. These high-temperature gas-cooled reactors (HTGRs) typically involve large numbers of tiny uranium fuel pellets encased in layers of carbon, silica, or both (designed to contain the fission products from the reaction). These pellets are generally pressed into larger fuel elements, which are either encased in solid graphite blocks or circulate through the reactor core in a so-called pebble bed system.[85]

Modern HTGRs are designed to be passively safe, offering the potential to avoid many of the complex, expensive safety systems used in LWRs. Moreover, HTGR concepts are being explored that would have lifetime cores - that is, they would be installed, switched on, and the operators would not have to do anything about fuelling or de-fuelling for the life of the

reactor. In combination, it is hoped that such features could lead to lower costs and improved safety. In what follows, design and performance issues for the pebble bed modular reactor (PBMR) are discussed to illustrate the possibilities that might be offered by HTGR technology.

The key to enhanced safety for the PBMR is a design that ensures that the highest temperature in the reactor core - under any conceivable operating or accident condition - never exceeds the 1,600 degrees Celsius operating limit of the fuel. This requirement limits the thermal output for a single module to 250 megawatts-thermal and the electrical output to 100 megawatts-electric - a factor of 10 smaller than for a typical LWR. The viability of the technology depends, among other things, on being routinely able to produce high-quality fuel particles and pebbles. There have been problems in the past in particle design and manufacturing, leading to release of radioactivity from the particles (NRC, 1992). In addition, the direct helium gas turbine cycle required with the PBMR is undemonstrated for a nuclear plant and requires substantial engineering (CISAC, 1995).

The spent fuel of the PBMR would be high-burn-up material in many tiny spheres, making it a comparatively unattractive source from which to recover weapons-usable material. Moreover, the PBMR and other HTGR variants could be operated on a denatured uranium-thorium once-through fuel cycle that would have the same proliferation and diversion resistance features as an LWR operated on this fuel cycle (Feiveson, von Hippel, and Williams, 1979).

The PBMR’s extraordinarily low power density[86] (a key safety feature) and modest scale will tend to drive up its specific cost (dollars per kilowatt-electric). But developers hope that these diseconomies will be offset at least partially by cost-saving opportunities - including design simplicity and system modularity that facilitate standardisation and realisation of mass production economies with a high fraction of the construction taking place in factories. Use of a closed-cycle helium gas turbine instead of a steam turbine for

energy conversion assists in this objective, because this turbine’s specific cost is lower and less scale-sensitive than the LWR’s steam turbine.

Eskom, the South African utility attempting to develop the technology (Nicholls, 1998), is targeting a capital cost of $1,000 per kilowatt-electric under mass production conditions for a power plant made up of a block of 10 100 MW_e modules. This is far less than the costs of $1,700 - 3,100 per kilowatt-electric that characterise today’s LWRs (Paffenbarger and Bertel, 1998). Despite the good prospects for cost cutting as a result of the PBMR’s attractive features (such as passive safety, modularity, and the relative scale insensitivity of the helium turbine’s capital cost), this is an aggressive cost target, considering the high capital cost for the reactor itself that is inherent in its low power density - which requires, for example, very large and costly reactor vessels that can withstand high operating pressures. An MIT group investigating the PBMR estimates a capital cost about twice that estimated by Eskom (NPPDP, 1998). Earlier independent estimates of the capital cost of other HTGR systems, such as the General Atomics system developed in the United States, tended to be consistently higher than the costs of LWRs, because of the low power density of the HTGR concept (NRC, 1992).

The technology is at too early a developmental stage to ascertain which of these estimates is closer to what can be expected in a commercial product. If the MIT estimate turns out to be close to the mark, the cost of electricity from this plant (table 8.15) would be about the same as for an coal integrated gasifier - solid oxide fuel cell - steam turbine power plant with CO_2 separation and sequestration (see table 8.9). If the cost turns out to be closer to the Eskom estimate, the direct economic balance would tip in favour of the PBMR. In such circumstances, other factors such as public attitudes towards waste disposal could be important determinants in the race between nuclear and fossil technologies to near-zero emissions.

In contrast to the approach being taken for advanced LWR development - an activity that

is well advanced; involves making only incremental, evolutionary changes relative to existing LWRs; and can build on a well-established industrial base - industrial activity relating to HTGRs is embryonic. No HTGR has yet been economically competitive. Nevertheless, the concept illustrates reasonable prospects for achieving at least the goal of demonstrable safety.

Nuclear energy for the long term

Uranium resource constraints might someday become important determinants of nuclear technology development. For the global high-nuclear-growth scenario discussed above, cumulative uranium requirements to 2050 with current technology are 3 million tonnes - less than reasonably assured resources recoverable at less than $130 a kilogram, so that resource constraints are not important in this period. But cumulative uranium requirements to 2100 for this scenario are close to the estimated 20 million tonnes of conventional uranium resources (including 12 million of speculative resources; chapter 5).

Thus, sometime after 2050, technology that can address the resource constraint challenge might have to become available under high-nuclear-growth conditions. Can advanced technologies address this potential constraint while simultaneously satisfying cost, safety, and proliferation and diversion concerns? In light of prospective long research and development gestation times and the need to make rational near-term research and development resource allocation decisions regarding post-2050 deployment options, it is important for this report to address this question. Five options are considered: conventional plutonium fast breeder reactors; alternative breeder concepts; extracting uranium from seawater; large-scale, interna-tionalised nuclear energy parks; and thermonuclear fusion.

Conventional plutonium fast breeder reactors

Until the mid-1970s, it was thought that uranium was scarce. Therefore, it was expected

that the LWR would be a stop-gap technology to provide start-up fuel for the fast breeder reactor (FBR), which by 1990 would overtake the LWR as the technology of choice for new plants (Lidsky and Miller, 1998).[87]

The LWR makes use of only 0.5 percent of the fission energy stored in natural uranium - primarily that in the fissile (chain-reacting) isotope U-235, which accounts for only 0.7 percent of natural uranium. The FBR would alleviate this constraint by transmuting a large fraction of the abundant fertile isotope U-238 through neutron capture into fissile isotopes of plutonium - making it possible to extract 50 - 100 times as much energy from a kilogram of uranium as the LWR. Among FBR options, particular attention was given to the liquid-metal (sodium) cooled fast breeder reactor (LMFBR), which offered the potential of being an effective fuel factory that could produce excess plutonium - adequate not only to sustain itself but also to serve as seed stock for a rapidly growing fleet of similar reactors.

The LWR-FBR vision has not materialised, and the prospects that it ever will are not bright. Although a few countries have FBR development programmes (China, France, India, Japan, Russia), these programmes are in virtual stasis. Most countries have abandoned once-ambitious programmes as a result of unpromising economics and a much brighter global outlook for uranium supplies (chapter 5) than when FBR programmes were originally put in place.[88] By the late 1970s it had become clear that FBR unit capital costs (dollars per kilowatt) would be much higher than for LWRs and that costs for fabricating MOX LWR fuel and FBR fuel would be far higher than previously projected. Life-cycle cost comparisons made at that time showed that the FBR could not compete with the LWR at then-projected uranium prices (Feiveson, von Hippel, and Williams, 1979). And now, with expectations that relatively low-cost uranium resources are far more abundant than was thought 20 years ago, it appears that the need for an FBR or alternative uranium-saving technology will not materialise before 2050, and possibly long after that (STATS, 1996).

TABLE 8.15. TWO ESTIMATES OF THE ELECTRICITY GENERATION COST FOR THE PEBBLE

BED MODULAR REACTOR (DOLLARS PER THOUSAND KILOWATT-HOURS)

Cost component	Estimate based on Eskom parameters[a]	Estimate based on MIT parameters[b]
Capital[c]	16.4	34.2
Operation and maintenance[d]	4.1	4.1+0.6[e]
Fuel	3.8	3.8
Total	**24.3**	**42.7**

Note: Estimates are for a 1,000 megawatt-electric plant made up of 10 100-megawatt-electric modules.
a. Data are from Nicholls, 1998. b. Data are from Kadak, 1999. c. For an annual capital charge rate of 11.5 percent and an 80 percent capacity factor. The unit capital cost estimated by Eskom and MIT analysts are $1,000 and $2,090 per kilowatt-electric, respectively. d. The staffing requirement for the plant is estimated to be 80 persons by Eskom (Nicholls, 1998) and 150 persons by MIT analysts (Andy Kadak, private communication, 8 September 1999). e. The $0.6 per thousand kilowatt-hours component of the cost is for decommissioning (Kadak, 1999).

Alternative breeder concepts

If uranium scarcity concerns should one day force a shift to breeder reactors, it would be desirable to have technologies that are simultaneously demonstrably safe and cost competitive and much more proliferation and diversion resistant than conventional liquid-sodium-cooled plutonium fast breeder reactors, which involve reprocessing spent fuel and recycling recovered plutonium in fresh reactor fuel.[89]

One set of such technologies is metal-cooled fast reactors, for which plutonium is never separated from fission products. One variant of the concept under investigation is a metal-cooled fast reactor using lead or a lead-bismuth eutectic instead of sodium as the liquid metal coolant (Filin and others, 1999, Hill and others, 1999; Lopatkin and Orlov, 1999; Orlov and others, 1999; Zrodnikov and others, 1999), building on Russian work carried out on lead-bismuth-cooled reactors for submarine applications.[90] Spent fuel reprocessing technology for these reactors would be designed to extract most fission products for waste disposal but leave 1 - 10 percent of the fission products plus plutonium and most transuranics in the reprocessed fuel that is returned to the reactor. The radiation hazard from residual fission products and transuranics would deter would-be proliferators and diverters.

Some natural or U-235-depleted uranium would be added to reprocessed fuel as source material to generate more plutonium in the reactor; the reactor would be designed to produce from uranium as much plutonium as it consumes.[91] A high level of burn-up of transuranics and long-lived fission products in the spent fuel could be achieved with repeated recycling and appropriate reprocessing technology - without the need for separate burners for transuranics and long-lived fission-products. Moreover, reprocessing plants might be co-sited with reactors, to eliminate proliferation and diversion risks associated with the transport of spent and reprocessed fuel. A modest-scale (100-megawatt-electric) version with a lifetime (15-year) sealed core has been proposed for developing country applications (Hill and others, 1999).[92]

Although this liquid metal reactor technology would deal effectively with the uranium supply constraint challenge and be more proliferation and diversion resistant than conventional plutonium breeder reactors, the reactors would have very large plutonium inventories - for example, 8 - 9 tonnes for a large 1,200-megawatt-electric design (Filin and others, 1999) and 2.5 tonnes for a small 100-megawatt-electric unit with a lifetime

reactor core (Hill and others, 1999).[93] Although the system would be designed so that plutonium would never be fully separated from spent fuel, such systems would provide their operators with extensive knowledge of, experience with, and facilities for chemical processing of intensely radioactive spent fuel, which could provide the basis for moving quickly to separating plutonium for a weapons programme should a decision be made to do so.

Moreover, for safeguards, either new measurement technologies would have to be developed to allow accurate material accounting for the intensely radioactive material involved in these fuel cycles, or almost complete reliance would have to be placed on containment and surveillance measures rather than material accounting. Hence, although such systems would certainly have higher inherent proliferation resistance than traditional reprocessing and recycling approaches involving fully separated, weapons-usable plutonium, the overall proliferation risks that might result from widespread deployment of these technologies across the globe are likely to be the focus of considerable debate in the technical community, should large-scale deployment ever seem a realistic possibility.[94]

Other alternative breeder concepts include molten salt thermal breeder reactors that would integrate continuous reprocessing for removal of fission products with reactor operations (Tinturier, Estve, and Mouney, 1999) and various particle-accelerator-based reactor concepts. Each seems to have one or more attractive features relative to conventional breeder reactor concepts, but all are technologies whose relative merits regarding cost, safety, proliferation-diversion risk, and waste disposal are the subject of intense debate in the technical community (NRC, 1992; CISAC, 1995).

Extracting uranium from seawater

If low-cost uranium resources are much more abundant than indicated by conventional uranium resource estimates (chapter 5), even high nuclear growth to 2100 and beyond

could be realised with proliferation and diversion resistant once-through fuel cycles. The recovery of uranium from seawater is one promising option for extending uranium resources; preliminary estimates of recovery costs are $100 - 300 per kilogram (chapter 5). Although the high estimated recovery cost is more than 10 times the current uranium price, it would contribute just $0.004 per kilowatt-hour to the cost of electricity for an HTGR operated on a once-through denatured uranium-thorium fuel cycle[95] - equivalent to the fuel cost for an oil-fired power plant burning oil priced at $2.50 a barrel!

Recovery of 15 percent of the uranium in seawater could support the year 2100 nuclear capacity level (6,500 gigawatts-electric) in the high-growth scenario (discussed above) for 1,000 years using such once-through reactor-fuel-cycle technologies. The key unresolved question is whether production of uranium from seawater could be carried out at acceptable cost at scales large enough to support a significant fraction of the world's nuclear capacity.

Large-scale, internationalised nuclear energy parks

If development of advanced proliferation- and diversion-resistant nuclear energy systems proves to be an elusive goal and the world opts for large-scale use of reprocessing and recycling technologies with substantial proliferation and diversion vulnerabilities, it might become necessary to cluster all the sensitive facilities - enrichment plants, reactors, reprocessing plants, fuel fabrication plants - in large, heavily guarded nuclear parks under international control to reduce the proliferation and diversion risks of nuclear fission. Electricity produced in such parks could be made available even to remote users through direct-current transmission lines. In addition, with reactors operated at suitably high temperatures (for example, high-temperature, gas-cooled reactors), hydrogen might also be produced as an energy carrier for world-wide energy commerce - initially perhaps by steam-reforming natural gas and ultimately with advanced thermal cycles that would use nuclear heat to extract hydrogen from water (Marchetti, 1976; Miyamoto and others,

1999; Scott and Hafele, 1990; Wade and Hill, 1999).

There is no doubt that this is technically feasible and would reduce proliferation and diversion dangers substantially. Much more questionable, however, is whether it is politically realistic to expect all the world's countries to place major components of their electricity supplies under international control - and to agree on the administrative arrangements for doing so.

Thermonuclear fusion

Another nuclear energy option for the very long term is thermonuclear fusion, based on exploiting the energy recovered in fusing light elements (for example, deuterium and tritium) rather than fissioning uranium or plutonium. The resources upon which fusion would depend - lithium and deuterium in seawater - are virtually inexhaustible.

How fusion compares with fission with regard to reactor safety, radioactive waste management, and proliferation and diversion risks depends on how the technology is developed. But relative to today's LWRs, it offers considerable promise, for three reasons (PCAST Fusion Review Panel, 1995). First, with regard to safety, population exposures to radiation from worst-case accidents are 100 times smaller than those from worst-case fission accidents. Second, with respect to radioactive waste hazards, those from fusion (on the basis of the most meaningful of indices combining volume, radiotoxicity, and longevity) can be expected to be at least 100 times and perhaps 10,000 or more times smaller than those from fission. Third, with regard to nuclear weaponry, electricity supply systems based on fusion would be less likely than fission systems to contribute to nuclear weapons capabilities acquisition by sub-national groups and, if designed appropriately, could be easier to safeguard against clandestine fissile material production by governments.

The essence of the potential

> The essence of the potential nuclear weapons link to fission power is that this technology provides the possibility of obtaining access to nuclear explosive materials.

Despite these advantages, it is still unclear whether fusion will eventually become a commercial energy technology. Even if technical goals can be realised, fusion is not expected to become an option for commercial energy applications before 2050 (PCAST Fusion Review Panel, 1995).

The outlook for addressing the challenges

Can the challenges related to nuclear power - cost, safety, proliferation and diversion, and waste management - all be adequately addressed with advanced technologies to make it widely acceptable? This question cannot be fully answered at this time - in part because consensus has not been reached on goals for technological innovation, and in part because the answer does not depend only on technical considerations.

Clarification of goals is needed to facilitate the development of a focussed nuclear energy innovation effort. The market, ideally with external costs internalised, will determine the competitiveness of future nuclear technologies, so that cost goals for the technology will have to be adjusted over time to respond to the changing competition. Although this uncertainty is common to all technologies, the intrinsic high investment cost required to bring new nuclear technologies to market makes this a continuing difficult challenge for nuclear power. Among externality concerns, consensus might converge on a goal of demonstrable safety (Lidsky, 1991).

However, goals relating to proliferation and diversion resistance and waste management

require considerable clarification. There is a strong technical case that LWRs operated on once-through fuel cycles are more proliferation and diversion resistant than today's reprocess-recycle technologies, but beyond that there is little agreement in the technical community as to the relative merits of alternative advanced concepts. For waste management, goals need to be better defined, not only to include various non-technical considerations but also to ensure that proliferation and diversion resistance goals are not compromised.

There seem to be reasonably good prospects for making reactors demonstrably safe while simultaneously also reducing cost - although this must be demonstrated, through appropriate research, development, and dissemination. This leaves proliferation and diversion and waste management - issues that also involve cost considerations. How much more proliferation and diversion resistant advanced nuclear technologies can be made relative to LWRs operated on once-through fuel cycles is unclear - as is the potential for maintaining even this degree of resistance in the future, when uranium might be much scarcer than it is today. But at least for the immediately future, there are no economic obstacles to making reactors at least as resistant to proliferation and diversion as LWRs operated on once-through fuel cycles.

A promising option for sustaining the proliferation and diversion resistance of reactors operated on once-through fuel cycles seems to be extraction of uranium from seawater. Because the technology probably will not be needed at least until sometime after 2050, there is no urgency to develop the technology. However, a critical near-term need is assessment of the feasibility of the concept at large scale to provide a more informed basis for prioritising research and development on alternative nuclear technologies for the long term.

Waste management is probably a technically soluble problem, but it is unclear whether promising technical fixes can be made broadly acceptable to the public. S&T technologies

for burning transuranics and long-lived fission products will probably get considerable research and development support as an option for addressing the waste disposal challenge - in large part because many people have little confidence in human capabilities to adequately manage waste risks for the long periods required (O'Neill, 1998) - even though S&T technologies are probably not necessary to adequately protect the public in the very long term. In a world where overall research and development investment funds are limited, such investments could limit funds available for other needed nuclear research and development activities.

In summary, for nuclear energy to qualify as a sustainable energy option, concerns regarding safety, waste disposal, and proliferation and diversion must be addressed in ways that enable nuclear energy to compete on an economic basis. Effectively addressing these concerns to enable a large expansion of nuclear power probably requires advanced technologies, as well as improved institutional risk management strategies.

Although it is possible to envision sets of nuclear technologies and management strategies that might fulfil the requirements for sustainability, decisions on future nuclear power will be made largely at the political level rather than on narrow technical and economic grounds. Gaining broad public support for nuclear power is not simply a matter of better educating the public on the issues, which is what many in the nuclear industry believe is needed most. The industry should also seek to better understand public concerns.[96] The industry must recognise that a stable political consensus on nuclear goals and strategies is needed to bring about a nuclear-intensive energy future. The industry should also consider opening up the nuclear decision-making process to diverse interest groups, so that a well-informed public could ensure that its concerns are addressed every step of the way (Bunn, 1999).

During the next 20 years there might be enough nuclear plant orders (mainly in Asia) and business opportunities associated with maintaining existing plants to keep the nuclear

industry from collapsing. But taking into account expected plant retirements, this period will probably be characterised by little if any net nuclear power expansion world-wide. The industry might consider this de facto moratorium on net expansion as a window of opportunity for confidence-building, through which it could seek to convince the public and investors that concerns about cost, safety, proliferation and diversion, and waste disposal can be dealt with effectively.

Although coping with the radioactive waste problem seems manageable from a technical perspective, a technical fix by itself is not a solution.

The number one priority on the confidence-building agenda is to reach a broad consensus on waste disposal policy. To get this consensus requires that industry engage effectively all stakeholder groups, including those ideologically opposed to nuclear power. Whether the needed deal-making is feasible or not is unknowable at this time, but not implausible. For example, as a strategy to deal with its strongest critics, industry leaders might consider becoming vocal supporters of public-sector-supported renewable energy and energy efficiency programmes in exchange for broad support for sensible nuclear waste management strategies and policies - in effect, giving the renewable and energy efficiency communities the opportunity (during the moratorium) to show whether they can deliver on what they hope for.[97]

If the energy innovation effort in the near term emphasises improved energy efficiency, renewables, and decarbonised fossil energy strategies,[98] the world community should know by 2020 or before much better than now if nuclear power will be needed on a large

scale to meet sustainable energy goals. With broad support for a sensible waste management strategy, the nuclear industry would be far better positioned to take off again at that time than if it were to continue dealing with its critics in a more confrontational manner.

In parallel with such confidence-building, the industry might consider strategies to prioritise the nuclear energy innovation effort. The first steps might include exploratory research and development (which is quite inexpensive relative to building large-scale demonstration projects) aimed at better clarifying the options.[99] These steps could be followed by efforts to reach consensus within the technical community regarding priorities, so that the industry would be well prepared to move ahead if the world community eventually decides that large-scale nuclear power is needed to meet sustainable energy goals.

Notes

1. Major reviewers for this chapter were Harry Audus (United Kingdom), Tim Brennand (United Kingdom), Ramon Espino (United States), Richard Garwin (United States), Chris Hendriks (Netherlands), Olav Kaarstad (Norway), Larry Lidsky (United States), Marvin Miller (United States), Larry Papay (United States), Jefferson Tester (United States), and Maarten van der Burgt (Netherlands).

2. Because methane is a powerful greenhouse gas (chapter 3), getting climate change benefits from shifting to natural gas requires minimising gas leakage from the entire gas system.

3. The Convention on Climate Change seeks to "achieve stabilisation of the greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame

sufficient to allow economic systems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" (UNFCC, 1992).

4. For example, the World Bank (World Bank, 1997) has estimated that in 1995 air pollution damages in China cost $48 billion, or 7 percent of GDP; see chapter 3.

5. In a study carried out under the auspices of the European Commission's ExternE Programme, Krewitt and others (1999) estimated that for the European Union (EU-15) the total cost of environmental damages arising from air pollutant emissions of fossil fuel power plants in 1990 was $70 billion, or more than $0.06 per kilowatt-hour of electricity generated; 97 percent of this cost is related to health - mostly fine-particle air pollution.

6. Uncontrolled emissions increase roughly in proportion to oil plus coal consumption, which in turn grows roughly in proportion to GDP. Assuming, as economists often do, that the willingness to pay to avoid health damages from air pollution increases as (GDP/P), it follows that the cost of health damages from uncontrolled emissions increases roughly as $P \bullet (GDP/P)^2$, where P = population.

7. The cost estimates presented in tables 8.1 and 8.2, like the estimates in Krewitt and others (1999), were developed under the ExternE Programme of the European Commission.

8. This gap exists for a variety of reasons - for example, regulated emission levels are for well-maintained cars, and regulations tend to be for driving cycles that often do not adequately reflect the way people actually drive cars (Ross, Goodwin, and Watkins, 1995).

9. To illustrate the challenge of addressing air quality goals as economies evolve, consider a simple model of a hypothetical average developing country that grows from its 1990

state, in which per capita GDP (GDP/P) = $2,300 (1990 dollars, purchasing power parity basis - the average for all developing countries in 1990) and there are no air pollutant emission controls in place, to a future state where per capita GDP is 7.2 times higher (GDP/P = $16,400, the average for countries belonging to the Organisation for Economic Co-operation and Development, or OECD, in 1990 - a level that could be realised in 100 years with a sustained 2 percent per year GDP/P growth rate). Suppose also that in this period per capita consumption of coal plus oil also increases 7.3 times, from the actual average level in 1990 for developing countries to the 1990 level for OECD countries, and that without controls pollutant emissions increase in proportion to coal plus oil consumption levels. Without pollution controls and taking into account an expected doubling of population in this period, health damage costs would increase about 100 times (2 x 7.2 x 7.3; assuming, as most economists do, that the willingness to pay to avoid pollution damages increases in proportion to per capita GDP). Thus end-of-pipe controls that reduce emissions by 99 percent would be required to keep damage costs in dollar terms to a level no greater than in 1990.

10. For example, the U.S. Department of Energy's Vision 21 Program (Clean Energy Plants for the 21st Century) seeks - in addition to achieving near-zero pollution emissions with advanced technology - reduced CO_2 emissions through both efficiency improvements and development of the capability to reduce CO_2 emissions to zero or near zero by means of CO_2 capture and sequestration. A complementary new DOE programme is carbon sequestration - a research and development effort aimed at developing carbon sequestration technologies to the point of deployment, so that these sequestration technologies will be ready to be deployed (if and when needed).

11. Efficiencies have been rising continually in conjunction with increasing turbine inlet temperatures, which have been rising at an average rate of 13 degrees Celsius a year for the past 30 years (Chiesa and others, 1993), as a result of more heat-resistant materials

being used for turbine blades and improved turbine blade cooling technologies.

12. On a lower heating value (LHV) basis, the efficiencies of the Frame 7F and Frame 7H are 56 and 60 percent, respectively.

13. Some regulations require controlling NO_x emissions to less than 10 parts per million, dry volume basis (at 15 percent O_2) - relative to typical uncontrolled emissions for natural-gas-fired systems of 125 parts per million.

14. In a typical gas turbine, two-thirds of the output of the turbine is needed to drive the compressor.

15. Spray intercooling has been applied to an existing gas turbine (without major modification) in a commercial product (McNeely, 1998). But this unit involves only 1 - 3 percent of the maximum feasible water injection rate.

16. The electricity generating potential through combined heat and power in a particular industry is the heat load times the characteristic output ratio of electricity to heat for the cogenerating technology.

17. These large syngas projects that involve electricity as a product or coproduct are part of a recent global inventory of syngas projected compiled by Simbeck and Johnson (1999) that involves 161 real and planned commercial-scale projects with a combined syngas production capacity of 60,880 megawatts-thermal. Many of these are polygeneration projects that involve the coproduction of various combinations of products - for example, electricity, steam for process, chemicals, town gas; and many of the projects are in the petroleum refining and chemical industries. About 44 percent of the productive capacity is based on coal; much of the rest is based on the use of low-cost petroleum refinery residues.

18. As an IGCC-based power industry grows, the benefit of by-product sulphur sales per kilowatt-hour will eventually decline when the sulphur supplies exceed demand, so that sulphur prices will fall.

19. For the cogeneration systems described in tables 8.7 and 8.8, condensing and extraction turbines rather than back-pressure turbines are needed; otherwise the ratio of electricity to heat production would be less than 1 to 1. (In condensing and extraction systems, some of the steam is bled from the turbine at the pressure appropriate for the process, and the rest of the steam is used to produce more power and then condensed; for the steam that is condensed, there is no cogeneration fuel-saving benefit.) The fraction of the steam that must be condensed is much greater in the steam turbine case than in the IGCC case, because of the much lower electricity-heat output ratios for steam turbines relative to combined cycles (see figure 8.1).

20. At present, gases exiting the gasifier at temperatures of 1,000 degrees Celsius or more are cooled to about 100 degrees Celsius to facilitate cleaning the gas of particulates and sulphur and nitrogen compounds. Then the cleaned gas is heated up to the turbine inlet temperature of 1,300 degrees Celsius or more.

21. Most of the rest will be used for standby service.

22. Because the temperature of the turbine exhaust is higher than that of the air exiting the compressor, the turbine exhaust heat is often recovered to preheat the air exiting the compressor before it is delivered to the combustor, so that moderate efficiencies are achievable despite the low pressure ratio.

23. Less than 0.24 grams per kilowatt-hour (9 parts per million by volume at 15 percent O_2) for the 28-kilowatt-electric Capstone Model 330 using a non-catalytic staged combustion system.

24. Ballard is a joint venture involving Ballard Power Systems, General Public Utilities International, and GEC Alsthom. Plug Power is a joint venture involving Mechanical Technologies, Inc., Detroit Edison, and General Electric.

25. An operating temperature in the range 700 - 800 degrees Celsius enables an efficiency increase of about 10 percent without compromising fuel flexibility and the process advantages offered by SOFCs operated at 1,000 degrees Celsius. A reduced operating temperature also leads to greater choice of electrode materials and reductions in system cost and complexity (Goldstein, 1992).

26. Oxygen would be needed for coal gasification, in any case.

27. Shell intends to use the technology in conjunction with its own oil and gas operations - including use of the separated CO_2 for enhanced oil recovery (SIEP, 1998).

28. To be effective in sequestering CO_2, aquifers need not be leak free. Lindeberg (1997) modelled CO_2 sequestration for injection during a 25-year period into aquifers for which there is an open boundary or fracture 8,000 metres from the injection well and showed that, if such aquifers have high permeability, some of the injected CO_2 would eventually escape. Assuming all CO_2 associated with future fossil fuel consumption (7,000 GtC) as projected in the IPCC's IS92a scenario (IPCC, 1995) is injected into such aquifers, Lindeberg estimated for the worst (leakiest) case that a fifth of the injected CO_2 would eventually leak out but would do so slowly over many centuries at climatically inconsequential rates - with leakage peaking in 3100 at 2 GtC per year; in contrast, if the same amount of CO_2 were released to the atmosphere during fossil fuel combustion, emissions would increase until they peak at 30 GtC a year in about 2150 and subsequently decline as fossil fuel resources are depleted.

29. All cases include costs to pressurise CO_2 to 135 bar plus a CO_2 disposal cost of $18 per tonne of carbon (equivalent to $5 per tonne of CO_2).

30. The calculation presented is an updated calculation for this decar-bonisation of fuel gas strategy originally advanced by Blok, Hendriks, and Turkenburg (1989) and van der Burgt, Cantle, and Boutkan (1992); also see Chiesa and Consonni (1998).

31. This is for disposal near the CO_2 separation site or for disposal with some credit for enhanced resource recovery. If the separated CO_2 had to be transported 500 kilometres to a remote aquifer for disposal, with no credit for enhanced resource recovery, the avoided cost would increase about another $10 per tonne of carbon (Williams, 1999b).

32. The system described in table 8.10 (based on Simbeck, 1999c) involves an autothermal reformer that uses steam and O_2 for reforming natural gas. Audus, Kaarstad, and Singer (1999) describe a system that instead uses steam and air for reforming, thereby avoiding the cost for air separation; their estimate of the CO_2 recovery cost penalty is less than two-thirds of the estimate in table 8.10. Simbeck (1999c) also estimates costs for autothermal reforming with steam and air but finds the cost to be higher than for reforming with steam and O_2, because savings from avoiding the cost of an air separation unit are more than offset by higher costs for downstream components that arise because the fuel gas is diluted with nitrogen from air.

33. For the advanced technology (2012) cases considered by Herzog (1999a), the lower heating value (LHV) efficiencies with CO_2 recovery and disposal are 55.6 percent for the NGCC case and 42.4 percent for the coal IGCC case, compared to 50.8 percent and 37.2 percent for the corresponding cases presented in table 8.10. The corresponding busbar costs in the Herzog analysis with 2020 U.S. fuel prices are $0.045 per kilowatt-hour for the NGCC case and $0.044 per kilowatt-hour for the coal IGCC case. (To put the Herzog

analysis on the same basis as the present analysis, Herzog's annual capital charge rate was changed from 15 to 11.5 percent, the capacity factor was increased from 75 to 80 percent, and a CO_2 transport-and-disposal cost - not taken into account by Herzog - of $5 per tonne of CO_2 was included.)

34. A litre of water contaminated with MeOH would contain a fatal dose if it were 2 - 7 percent MeOH by weight.

35. The cetane number is a measure of a fuel's ability to auto-ignite. A high cetane number is desirable for candidate fuels for compression-ignition engines because it shortens ignition delay, lowering premixed burning and resultant NO_x emissions and noise. High octane fuels have low cetane numbers, and fuels with high cetane numbers have low octane ratings.

36. This plant commenced operations in 1993 but was shut down in late 1997 by an explosion at the air separation plant (from the build-up of small particles taken in from the air - apparently as a result of the prolonged haze that had blanketed the entire South Asian region in late 1997). The plant is scheduled to reopen in 2000, after repairs are completed.

37. These increased emissions of especially small particles appear to arise as a result of controlling soot particle emissions - which dominate the mass of particulate emissions - using current technology. Removing soot particles thereby removes nucleating agents on which these tiny particles would otherwise condense or adsorb; these very small particles seem to come from ash in the lubricating oil (Abdul-Khalek and others, 1998).

38. The calculations presented in tables 8.11 and 8.12 are based on well-established cost estimates and cost-scaling exponents for each of the many components of these systems. However, it is assumed in these calculations that each component (for example, the coal

gasifier) can be built in a single train to the required capacity. The maximum sizes of single-train components that are commercially available today are less than the capacities associated with many of the components for the polygeneration systems presented in these tables. To the extent that multiple trains instead of single trains would have to be used for practical systems, the cost savings would be less than indicated in tables 8.11 and 8.12. But these tables illustrate the value of evolving towards systems based on large single-train systems and thus represent good targets for development.

39. Air Products and Eastman Chemicals tested liquid-phase MeOH production technology in a process development unit at LaPorte, Texas, which was designed to produce 6,900 litres per day and which operated for 7,400 hours. Following this, a commercial-scale plant (designed to produce 288,000 litres per day) went into operation in January 1997, at Kingport, Tennessee, under the U.S. Department of Energy's Clean Coal Technology Program, to demonstrate the technology during a period of 4 years of expected plant operation.

40. In China more than 20 Texaco gasifiers are operating, under construction, or on order for the production of chemical fertiliser, MeOH, town gas, or oxochemicals. In addition, 6 Shell gasifiers and at least 1 Lurgi gasifier are being used to produce ammonia (NH_3) from coal.

41. Water or steam injection would probably not be pursued for gas turbine and steam turbine combined cycles because these options would reduce efficiency. However, the technique would be appropriate for low-capital-cost systems that use steam or water injection for efficiency augmentation - such as intercooled steam-injected gas turbines (Williams and Larson, 1989) or, for water injection, Tophat® cycles (van Liere, 1998).

42. Consider H_2 manufacture from coal - a process that begins with O_2-blown coal

gasification, which is also the first step in processing coal for IGCC plants. Just as pollutant emissions from coal IGCC plants are almost as low as from NGCC plants (see table 8.1), pollutant emissions from H_2 production plants are expected to be very low. Pollutant emissions per unit of coal consumed would tend to be lower than for IGCC plants, because gases exiting the gasifier must be cleaned to a higher degree to protect catalysts in downstream processing equipment from damage by contaminants such as sulphur. Catalyst protection requirements are often more stringent than regulatory requirements for air pollutant emissions.

43. For example, it is estimated that at a future (optimistic but plausible) photovoltaic electricity price of \$0.027 per kilowatt-hour, the cost of photovoltaic-derived H_2 would be \$17 per gigajoule (IPCC, 1996a). For comparison, the cost of making H_2 from natural gas and coal today, including the cost of storing the separated CO_2 underground, is \$6 per gigajoule for natural gas and \$11 per gigajoule for coal (Kaarstad and Audus, 1997). With advanced fossil-energy conversion technologies that are likely to be available by the time a photovoltaic electricity price of \$0.027 per kilowatt-hour is reached, fossil-energy-derived H_2 costs with CO_2 sequestration would be less (Williams, 1999b). (Even credit for the by-product O_2 generated in electrolytic processes would not help much; such a credit would amount to only about \$0.60 per gigajoule of electrolytic H_2 (\$20 per tonne of O_2) assuming an installed cost of \$21.60 per tonne of O_2 per day for an air liquefaction plant).

44. An H_2 fuel cell car would typically be three times more fuel-efficient than a conventional gasoline internal combustion engine car of comparable performance. This efficiency gain arises because, while the efficiency of an internal combustion engine declines with decreasing load (so that the efficiency of driving a car, averaged over all driving conditions, is a modest 15 percent), the efficiency of a fuel cell increases as the load decreases (so that the efficiency at average part-load conditions is a high 50

percent).

45. Some indicators of the level of industrial effort to develop fuel cell vehicles: by the end of 1999 the four largest Japanese manufacturers had spent $546 million on fuel cell development. Honda has announced plans to spend up to $500 million on fuel cell research and development during the next five years. DaimlerChrysler has spent $300 million on fuel cells and expects that it will have spent $1.4 billion by 2004, when it starts producing engines for fuel cell vehicles.

46. For F-T liquids production, syngas with an H_2 to CO ratio of 2 is needed. Because steam reforming instead gives a ratio of 3 ($CH_4 + H_2O \rightarrow CO + 3H_2$), syngas is typically made through partial oxidation ($CH_4 + 1/2\ O_2 \rightarrow CO + 2H_2$), which gives the right ratio but requires an expensive air separation plant. When some CH_4 is instead used to produce H_2, the CO_2 by-product can be used for doing some CO_2 reforming ($CH_4 + CO_2 \rightarrow 2CO + 2H_2$), along with steam reforming, to get the right overall ratio, thereby avoiding the need for an air separation plant.

47. The process of making H_2 from syngas (mainly CO and H_2) involves reacting the CO with steam (in water-gas shift reactors) to produce H_2 and CO_2. With current technology, this is followed by the use of capital-and energy-intensive equipment to separate the H_2 and CO_2.

48. As indicated in chapter 5, global methane clathrate hydrate occurrences have an energy content of 780,000 exajoules (table 5.7) and a carbon content of 12,000 GtC (table 5.8). If half of this resource could ultimately be recovered and burned along with 5,000 GtC of fossil energy reserves and resources (table 5.8), and if half the released CO_2 stayed in the atmosphere, the atmospheric CO_2 level would be eight times higher than at present.

49. The announced efficiency is on an LHV basis, and the design is for once-through processes using cold seawater under wintertime conditions for northern Europe and does not include energy penalties for pollution control. Correcting to the norm of 40 millibar (29 degrees Celsius) of the International Standards Organization for once-through cooling with steam condensation, accounting for fuel consumption requirements for air pollution control equipment that would lead to low levels of SO_2 and NO_x emissions, and converting to a higher heating value basis (the norm for this report), the efficiency would be about 43 percent (see entry in the first row of table 8.9).

50. Because cogeneration systems involving condensing heat transfer are less costly than those requiring steam cooling, reheat steam cycles (which deliver superheated steam) are typically not attractive (Kovacik, 1996).

51. The air separation plant contributes $150 per kilowatt-electric to the capital cost of an IGCC plant and requires 12 percent of gross power output for operations (Simbeck, 1999a).

52. Advanced clean-up technologies being pursued operate at 500 - 600 degrees Celsius, well below the temperatures of gases exiting the gasifiers - so that the process is described as warm rather than hot.

53. The U.S. Department of Energy - supported demonstration project aimed at proving warm gas clean-up for IGCCs with air-blown gasification (a 100-megawatt-electric Pinon Pine IGCC Power Project in Nevada that was put into service in early 1997) had sustained operating runs of less than 13 hours as of June 1999 (Motter, 1999).

54. But air-blown gasifiers are well-suited for biomass IGCCs (Simbeck and Karp, 1995; Williams and Larson, 1993); low sulphur and nitrogen contents of typical feedstocks make biomass a good candidate for warm-gas cleanup. In addition, scale economies make air

separation costly at the relatively small scales of most biomass power applications.

55. Heating up the extra mass of N_2 in combustion leads to lower peak flame temperatures for air-blown units.

56. In fluidised-bed combustion, fuel is burned in a bed of fuel and other materials that behaves like a fluid, as a result of a gas passing upwards through the bed fast enough to support fuel and other particles but not so fast as to transport particles out of the bed. Typically 2 - 3 percent of the weight of the bed material is coal.

57. Second-generation technology, which is entering the pilot and demonstration phases, will employ a coal pyrolyser to produce, from some of the coal input, fuel gas that is burned in a gas turbine combustor so as to increase the turbine inlet temperature of the gases delivered to the gas turbine.

58. Still another source of greenhouse gas emissions arises because all carbon in the limestone added to an AFBC unit for sulphur removal (limestone is typically added at two or more times the rate theoretically required for sulphur removal) is released as CO_2 at levels that could be significant for high-sulphur coals. The problem is less for PFBC units, which can be designed to suppress CO_2 emissions from the quantities of limestone present in the bed at levels in excess of the theoretical amounts needed for sulphur removal. In both cases these extra CO_2 emissions are not significant in practice because the use of high-sulphur coals is not practical for fluidised-bed combustion units.

59. The need for H_2 arises from the H-C ratio of 2 for today’s hydrocarbon fuels, relative to 0.8 for coal.

60. In 1996, more than 75 percent in France and Lithuania, and more than 50 percent in Belgium and Sweden.

61. The reference scenario of the Energy Information Administration (EIA) of the U.S. Department of Energy is that nuclear capacity will be 311 gigawatts-electric in 2020; the low-growth and high-growth EIA scenarios for 2020 project 179 and 442 gigawatts-electric of nuclear capacity, respectively (EIA, 1999a). The most recent forecast of the International Atomic Energy Agency (IAEA) is that nuclear capacity in 2020 will be 305 - 582 gigawatts-electric, with its share in total power generation falling by then to 10 - 14 percent (IAEA, 1999).

62. There is a considerable range in nuclear forecasts for individual countries. For Japan in 2010, the EIA (1999) projects 39.6 - 54.8 gigawatts-electric, with a reference value of 47.5 gigawatts-electric - relative to 43.9 in 1997. In contrast, the official (Ministry of Trade and Industry) projection for Japan in 2010 is 70 gigawatts-electric (Matsuoka and Hiranuma, 1998); others project 55 - 60 gigawatts-electric or less (Hard, 1997; Hagen, 1998). For China in 2010, the EIA (1999a) projects 8.7 - 11.5 gigawatts-electric, with a reference value of 11.5 gigawatts-electric - up from 2.2 in 1997. The Chinese National Nuclear Corporation has projected a total installed capacity of 20 gigawatts-electric by 2010; however, this might not be achieved, as a result of both overall excess electric generating capacity and the high costs of nuclear expansion.

63. The Rabl and Spadaro damage cost estimates include consideration of severe reactor accidents, for which they assumed a reactor core melt probability of 10^{-5} per year with a release of 1 percent of the radioactivity in the core in an accident - corresponding to the reference accident scenario used by French national safety authorities. According to the authors, the calculations assume "a mature and stable political system, with strict verification of compliance with all regulations."

64. This scenario involves net new nuclear generating capacity being added at an average rate of 62 gigawatts-electric per year during the next 100 years, and, if nuclear plants last 40 years, a corresponding average rate of nuclear plant construction (including

replacement capacity) of 115 gigawatts-electric per year. For comparison, the nuclear capacity in the most nuclear-intensive IIASA-WEC scenario (A3) is 6,000 gigawatts-electric in 2100 (chapter 9).

65. Assuming 50 percent efficient coal plants and 60 percent efficient natural gas plants.

66. Cumulative CO_2 emissions for the IPCC’s IS92a scenario are 1,500 GtC, 1990 - 2100; or 1,420 GtC, 2000 - 2100 (IPCC, 1995).

67. This gloom-hope perspective on the prospects for nuclear power is widely shared by governments. In the text agreed to by government delegations at the final plenary session for Working Group II of the IPCC’s second assessment report, it is stated that "nuclear energy could replace baseload fossil fuel electricity generation in many parts of the world if generally acceptable responses can be found to concerns such as reactor safety, radioactive waste transport and disposal, and nuclear proliferation" (IPCC, 1996b). Similarly, the Energy Research and Development Panel of U.S. President Clinton’s Committee of Advisors on Science and Technology concluded: "Several problems cloud fission’s potential as an acceptable power source today and into the future: disposal of radioactive waste; concern about nuclear weapons proliferation; concern about safe operation of plants; and noncompetitive economics…Given the projected growth in global energy demand…and the need to stabilize and then reduce GHG emissions, it is important to establish fission energy as an acceptable and viable option, if at all possible…Therefore, R&D is needed to solve the problems" (PCAST Energy Research and Development Panel, 1997).

68. Assuming a 10 percent discount rate, the value assumed in assessing all technologies in chapter 8. For a 5 percent discount rate, this report projected costs of $1,400 - 2,800 per kilowatt-electric (Paffenbarger and Bertel, 1998).

69. The high cost and complexity of the LWR are related in part to its high power density - ironically the reason it was originally chosen for submarine use!

70. For example, the former chairman of the Atomic Energy Board of India was warned that the safety status of nuclear energy installations in India is far below international standards, and that in the absence of an independent regulatory body this has serious implications for public safety (Gopalakrishnan, 1999).

71. Nuclear-explosive materials are those that can sustain a fission chain reaction based on fast neutrons, which is the requirement for making a nuclear bomb. The two principal nuclear-explosive materials are mixtures of uranium isotopes that contain more than 20 percent of the fissile isotopes U-233 and U-235; and all mixtures of plutonium isotopes, except those containing a high proportion of Pu-238 (see CISAC, 1995).

72. The importance of complementing institutional measures with technological strategies was underscored recently by Evgeniy Adamov, the Russian minister of atomic energy, who has expressed the view that the risk of diversion of nuclear material is one of the key problems of the nonproliferation regime, and therefore, "no matter how efficient the inspection and safety regime in different countries may be, it is necessary to pass on to a different kind of technological cycle in nuclear energy that has built into it a mechanism to prevent the development of weapons-grade materials" (press conference transcript, 25 November 1998).

73. On the institutional side, continuing efforts are under way to strengthen the international safeguard system, export controls over key technologies, and security systems designed to prevent the theft of weapons-usable nuclear materials. Much more remains to be done in each of these areas, however - particularly because the collapse of the Soviet Union has greatly weakened controls over technologies, information, and materials in the former Soviet states. In the case of the international safeguards regime,

the IAEA is critically in need of more resources, having been on a near-zero-real-growth budget even while taking on substantial new responsibilities, and the IAEA also requires strong political support to effectively implement the new safeguard measures agreed to in recent years. R&D is also needed to improve safeguard technologies, including those designed to detect clandestine nuclear activities from kilometres away and those to account more accurately for plutonium in spent fuel and in bulk processing (as occurs during reprocessing and plutonium fuel fabrication), as well as highly enriched uranium in bulkpro-cessing. For a detailed discussion of institutional strategies for reducing proliferation risks associated with nuclear power, see Walker (1999).

74. In addition, India has a small pilot reprocessing plant at Tarapur and has recently put into operation a second reprocessing plant at Kalpakkam. And Japan has a small reprocessing plant at Tokai Mura (currently shut down). Under the Carter administration, the United States abandoned plans for fuel reprocessing and plutonium recycling as a result of both nuclear proliferation concerns and poor prospective economics. Since 1990 the Russian reprocessing plant has been running at a modest fraction of its rated capacity; some of its non-Russian clients have shifted from a spent fuel reprocessing strategy to a direct spent fuel disposal strategy, and Russian reactor operators are failing to pay their bills (Berkhout, 1998).

75. For the Russian Federation’s reprocessing plants, the situation is somewhat more complex. There does not appear to be a requirement for plutonium return. Older contracts do not appear to require return of high-level wastes; high-level waste return appears to be required by at least some interpretations of Russian law, but the law is being ignored.

76. At today’s low uranium market price of $25 per kilogram (equivalent to an oil price of less than $0.30 per barrel), the purchase of uranium contributes to the cost of nuclear electricity less than $0.0005 per kilowatt-hour. A 1994 study estimated that the levelised fuel cost for the once-through LWR fuel cycle is 14 percent less than for the reprocessing

cycle (NEA, 1994). A more recent analysis found reprocessing and plutonium recycling to be much less attractive economically and estimated that uranium prices would have to increase by six times before reprocessing and recycling would be economic (Fetter, Bunn, and Holdren, 1999).

77. A variety of other possibilities have been considered over the years and might still be pursued someday as alternatives to repositories, including disposal in the seabed, in miles-deep drilled boreholes, in space, and the like.

78. This cost assessment is consistent with a Framatome assessment that a particle-accelerator-based system that would transmute minor transuranics and long-lived fission products would not be competitive in electricity generation with LWRs (Vale, 1999).

79. For example, it has been recently discovered that water moves through the mountain much faster than had been thought, and thermal inclusions have been identified that may (or may not) suggest upwellings of water in the not very distant past.

80. During a period of 500,000 to 1 million years, the most exposed community 30 kilometres from Yucca Mountain (if that site becomes a U.S. nuclear waste repository) may have exposure from groundwater that is comparable to background radiation. However, only a tiny fraction of the population would be so exposed.

81. For example, recent measurements challenge the widely held technical view that the greatest long-term waste disposal hazards arise not from transuranics but from long-lived fission products. The relative lack of concern about transuranics arises from the belief that even if storage canisters eventually lose their integrity, the transuranics will not dissolve readily in reservoir groundwater because they are quite insoluble relative to long-lived fission products under both oxidising and reducing conditions. Thus, except where there would be human intrusion into the repository, the main doses to humans after long periods would be from the long-lived fission products Tc-99 and I-129, which are soluble

and thus can move through groundwater pathways (STATS Committee, 1996). But recently, trace plutonium contamination was discovered in sub-surface waters in Nevada that can be unambiguously identified as having come from a nuclear weapons test 30 years earlier at the Nevada test site 1.3 kilometres from the point where the plutonium contamination was found. This measurement (Kersting, 1999) and related tracer experiments (McCarthy, Sanford, and Stafford, 1998) suggest that sub-micron-scale colloidal particles are the carriers of plutonium through groundwater. In addition, it has recently been shown that water, even at ambient temperatures, can further oxidise PuO_2 into forms for which more than 25 percent of the Pu ions exist in states that are far more soluble (Haschke, Allen, and Morales, 2000). Although these findings do not prove that such mechanisms will provide significant exposure pathways from nuclear weapons test sites or radioactive waste disposal sites, they do show that concerns about long-term waste disposal are made up of technical as well as political elements (Honeyman, 1999; Madic, 2000).

82. Vendors of heavy water reactors are also developing evolutionary advanced designs, with features similar to those being incorporated into evolutionary advanced light water reactor designs.

83. U-233, like U-233 and Pu-239, is a fissile material from which nuclear weapons can be readily made.

84. Relatively pure U-233 might be obtained by extracting chemically from spent fuel the Pa-233 precursor of U-233 before the Pa-233 (with a 27-day half-life) has a chance to decay (Glaser, 1998). Glaser (1998) also points out that if a would-be had access to relatively modest-scale uranium enrichment capacity, weapons-grade uranium could be produced from both the U-233 and the U-235 in the denatured fuel, because most of the separative work required to produce weapons-grade uranium from natural uranium has already been carried out.

85. The type of HTGR involving fixed graphite blocks has been the focus of considerable effort in several countries (including construction and operation of prototype reactors with varying degrees of success); an international consortium including France, Japan, the Russian Federation, and the United States is developing a next-generation modular design of such a system, with the idea of possibly constructing a prototype in the Russian federation. The pebble bed variant of the HTGR has been the focus of development in several countries (including construction and operation of an early prototype in Germany some years ago), and a pebble bed modular reactor is now the focus of an embryonic international effort led by Eskom, the electric utility of South Africa, with particiaption from German experts and MIT, among others.

86. Less than 4.5 megawatts per cubic metre, relative to 100 megawatts per cubic metre for an LWR.

87. The nuclear LWR-FBR nuclear vision was epitomised by the US Atomic Energy Commissions' 1973 projection that by 2000 the United States would get half its electric power from 400 FPRs and 600 LWRs.

88. The United States abandoned the 300-megawatt-electric Clinch River Breeder Reactor demonstration project in 1983, after spending $7 billion, and cancelled the follow-on Integral Fast Reactorin 1994. The United Kingdom completed an FBR prototype in 1974 but shut it down in 1994, after abandoning plans for construction of a follow-up full-scale demonstration project. France completed the 300-megawatt-electric Phenix prototype FBR in 1973 and $5 billion full-sized, 1,200-megawatt-electirc Super Phenix in 1985. Although the Phenix has been relatively trouble free, the Super Phenix has been shut down for long periods as a result of sodium leaks and related safety issues, and the French government recently announced that the Super Phenix will be dismantled. Germany completed an FBR progamme; a sodium coolant accident at the Monju prototype FBR in 1995 has put the Japanese FBR programme largely on hold, although some variant of the plutonium FBR

remains a major objective of Japanese nuclear energy policy (Hori and others, 1999). The Russian Federation operates the world's only remaining commercial-scale breeder (the BN-600 at Beloyarsk) and has the world's only remaining plans for near-term construction of additional commercial breeders (the BN-800), but construction of these has been stopped for many years for lack of funds. The BN-350 breeder reactor in Kazakhstan was recently closed, with no plans for replacement.

89. Consider implications for plutonium management if the world nuclear industry evolves according to the high-nuclear-growth scenario given above, with 6,500 gigawatts-electric of installed nuclear capacity in 2100. Suppose also that, by that time, uranium resource constraints will have led to a decision to introduce conventional plutonium recycling. Each one-gigawatt-electric power plant under such circumstances would discharge in its spent fuel 10^3 kilograms of plutonium each year that would be recovered via reprocessing and used in fresh fuel. The amount of plutonium circulating in global commerce would be 6.5 million kilograms per year. The amount of plutonium needed to make a nuclear weapon is less than 10 kilograms. Because of the daunting institutional challenges associated with preventing significant quantities of this plutonium from being diverted to weapons purposes, it would be desirable to have available more proliferation-and diversion-resistant nuclear technologies that would not be so difficult to manage institutionally.

90. Two ground-based reactor test facilities were constructed, and eight nuclear submarines powered with lead-bismuth-cooled reactors were built (Crodnikov and others, 1999).

91. In constrast to conventional plutonium breeders, for which plutonium production targets are greater than plutonium consumption rates.

92. The reactor for the proposed system would be compact (with a core volume of 6.8 cubic metres). The reactor core would be sealed so that individual fuel assemblies could

not be removed. The entire sealed core could be delivered as a unit to the power plant site and returned to the factory at the end of its useful life.

93. High security would have to be provided to deter theft of sealed reactor cores during transport to (as well as from) deployment sites.

94. It would take 10 - 15 years to develop and build an experimental reactor and 20 years before a demonstration unit could be put into operation (Orlov and others, 1999). Thus, even with a dedicated effort, deployment could not take place for decades.

95. Assuming a 1970s-vintage version of this technology, for which the uranium fuelling requirements (with a tails assay of 0.1 percent U-235 at the uranium enrichment plant) are estimated to be 13.5 times 10^{-6} kilograms per kilowatt-hour, which is 64 percent of the uranium fuelling required for an LWR (Feiveson, von Hippel, and Williams, 1979).

96. To this end, Bunn (1999) sees the need for independent research by social and political scientists on the roots of public attitudes on nuclear technology.

97. Such a strategy was suggested by Lidsky and Cohn (1993).

98. In contrast to the situation for the renewables and energy efficiency communities, those seeking expanded roles for fossil fuels in a greenhouse-gas-constrained world probably do not need political support from the nuclear industry to get a fair chance to prove whether or not decarbonised fossil energy strategies are viable.

99. This strategy was also suggested by Lidsky and Cohn (1993).

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