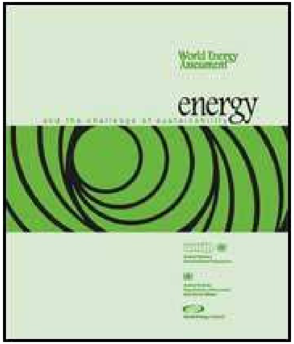

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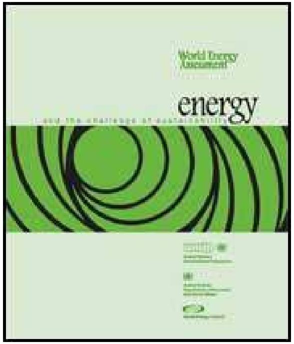

World Energy Assessment

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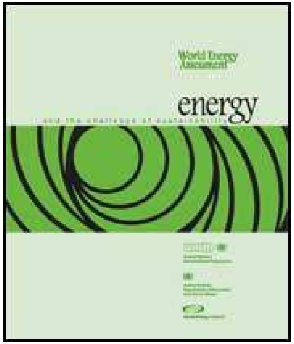

Annex. Case studies of crop-residue-derived modern energy carriers in China

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PART III: ARE SUSTAINABLE FUTURES POSSIBLE?

Chapter 9. Energy Scenarios

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ABSTRACT

Energy scenarios provide a framework for exploring future energy perspectives, including various combinations of technology options and their implications. Many scenarios in the literature illustrate how energy system developments will affect the global issues analysed in part 1

(chapters 1-4). Some describe energy futures that are compatible with sustainable development goals, such as improved energy efficiencies and the adoption of advanced energy supply technologies. Sustainable development scenarios are also characterised by low environmental impacts (local, regional, global) and equitable allocation of resources and wealth.

The three cases of alternative global developments presented in this chapter suggest how the future could unfold in terms of economic growth, population trends, and energy use. The challenge is formidable. For example, by 2100, 6-8 billion additional people - significantly more than the world population today - will need access to affordable, reliable, flexible, and convenient energy services. All three cases achieve this, through different energy system developments, but with varying degrees of sustainability.

A middle-course reference case (B) includes one scenario and is based on the direction in which the world is headed. Assuming continued moderate economic growth and modest technological improvement, this scenario leads to adverse environmental impacts, ranging from regional acidification to climate change. Thus - although it is a substantial improvement over the current situation - this scenario falls short of achieving a transition towards sustainable development. The other two cases and their variants lead to higher levels of economic development

with vigorous improvement of energy technologies. They both - especially the ecologically driven case (C) - also result in a transition towards sustainable development.

Case A includes three scenarios with high economic growth throughout the world. One of them, A3, achieves some sustainable development goals through rapid economic growth in conjunction with a shift towards more environmentally benign energy technologies, including a significant role for clean fossil, renewables, and nuclear energy. The other two lead to a higher dependence on carbon-intensive fossil fuels, resulting in high energy-related emissions - and so are unsustainable.

Case C includes two ecologically driven scenarios with high growth in developing countries (towards being rich and 'green'). One of them, C1, assumes a global phaseout of nuclear energy by 2100. The other, C2, does not. Both assume that carbon and energy taxes will be introduced to promote renewables and end-use efficiency improvements - rather than to reduce other taxes in industrialised regions.

The considerable differences in expected total energy consumption among the scenarios reflect varying approaches to addressing the need for energy services in the future and demonstrate that policy matters. Increases in research, development, and deployment efforts for new energy technologies are a prerequisite for the achievement of the three

scenarios that have characteristics of sustainable development. Significant technological advances will be required, as well as incremental improvements in conventional energy technologies. In general, scenarios A3, C1, and C2 require significant policy and behavioural changes in the next few decades to achieve more sustainable development paths. Taken together, these changes, which are described in more detail in part 4 (chapters 11 and 12), represent a clear departure from a business-as-usual approach.

Another crucial prerequisite for achieving sustainability in the scenarios is near-universal access to adequate and affordable energy services and more equitable allocation of resources. Finally, environmental protection - from indoor pollution to climate change - is an essential characteristic of sustainable development in the scenarios. The resolution of these future challenges offers a window of opportunity between now and 2020. Because of the long lifetimes of power plants, refineries, and other energy-related infrastructure investments, there will not be sufficient turnover of such facilities to reveal large differences among the alternative scenarios presented here before 2020. But the seeds of the post-2020 world will have been sown by then. Although choices about the world's future energy systems are now relatively wide open, they will narrow by 2020, and development opportunities, such as achieving sustainability, might not be achievable later if forgone today.

Sustainable development has become a synonym for desirable transitions into the new millennium. This is often reflected in energy scenarios that consider conditions for achieving sustainable development. Because energy systems change slowly, energy scenarios have long time horizons - often extending more than 100 years into the future. These long time periods are needed to formulate transitions to sustainable development paths. And because energy is also an important prerequisite for sustainability, there is a large body of literature on energy scenarios that describe sustainable development paths.

This chapter assesses that literature and summarises the main driving forces of future energy developments and their implications. The objective of the chapter is to link - through global scenarios - the energy options presented in part 2 (chapters 5-8) with the salient energy issues presented in part 1 (chapters 1-4), thereby illustrating the conditions for sustainable futures. Three global scenarios (A3, C1, and C2) are considered that to varying degrees lead towards sustainability. All of them require polices and measures in the near future to accomplish the envisaged transition, and none is compatible with current trends. They are compared with a third reference scenario (B) that also outlines positive future developments but lacks many of the characteristics of sustainability. This scenario is more consistent with current developments and trends. These three scenarios have been developed jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC)

and are presented here to represent a wider literature on reference and sustainable development scenarios (IIASA-WEC, 1995; Morita and Lee, 1998; Nakicenovic, Grbler, and McDonald, 1998; Nakicenovic, Victor, and Morita, 1998).

What are scenarios and how are they used for energy assessments?

Scenarios are images of alternative futures. Scenarios are neither predictions nor forecasts. Each scenario can be interpreted as one particular image of how the future could unfold. Scenarios are useful tools for investigating alternative future developments and their implications, for learning about the behaviour of complex systems, and for policy-making.

Energy systems are complex, their behaviour may be uncertain and is not always well understood, and information on them is often incomplete. Frequently scenarios are the best tool for understanding alternative energy developments and their implications. In scientific energy assessments, scenarios are usually based on an internally consistent, reproducible set of assumptions or theories about the key relationships and driving forces of change, which are derived from our understanding of both history and the current situation. Often such energy scenarios are formulated with the help of formal models. More than 400 quantitative energy scenarios are documented in the database developed by Morita and Lee (1998).

Formal models cannot, however, capture all aspects of energy systems. Some aspects of energy perspectives can only be appreciated through intuition and are best communicated by images and stories. Thus scenarios are sometimes less quantitative and more descriptive, and in a few cases do not involve any formal analysis and are expressed in qualitative terms. Energy scenarios can also involve components of both; they sometimes have a narrative part, often called a "storyline", and a number of corresponding quantitative scenarios for each storyline. Some scenarios are primarily narrative and qualitative, even if actual numbers are used for illustrative purposes. This is often the case with energy scenarios that prescribe the achievement of sustainability and thus make particularly strong assumptions about the future.

Each scenario can be interpreted as one particular image of how the future could unfold.

Scenarios are not value free, and can often be divided into two broad groups: descriptive and normative. Descriptive scenarios are evolutionary and open-ended, and explore paths into the future without any preconceived endpoint. Normative (or prescriptive) scenarios are explicitly values-based and teleological, and explore the routes to desired or

undesired endpoints (utopias or dystopias). The distinction between the two groups is not always clear (Nakicenovic and others, 2000). For instance, two of the three scenarios from the International Institute for Applied Systems Analysis and World Energy Council (IIASA-WEC) that are considered here describe how many conditions of sustainability could be achieved by the end of the 21st century but also contain many normative elements that illustrate polices and measures that would be required to change current trends.

Alternative development paths and how they are reflected in scenarios

The starting point for any analysis of energy development is a prospective look into the future. Because it is impossible to predict future energy developments, an important purpose of alternative energy scenarios is to analyse possible global and regional developments for periods of a century or more so that their implications for sustainable development can be assessed. For now, these long-term energy scenarios are the best way to integrate demographic, economic, societal, and technological knowledge with our understanding of ecological systems and environmental implications. As an integration tool, scenarios also allow a role for intuition, analysis, and synthesis. By developing scenarios, researchers can analyse future determinants of energy requirements and compare them to supply availabilities, financing, environmental constraints, and other salient factors and driving forces. Long-term scenarios can provide a

framework for a 'retrospective view from the future' and for assessing near-term measures to achieve sustainable and other desirable development paths.

The traditional method of formulating scenarios first involves developing a 'business-as-usual' baseline that essentially assumes that things will not change in the future; then 'policy' cases starting from the baseline are developed. But it is becoming increasingly evident that it is next to impossible to formulate future developments that do not include any change in comparison with today; namely, futures that capture the business-as-usual course of events. In fact, even though energy futures are unpredictable, one thing that appears almost certain is that the future will be different from today. In addition, it is virtually impossible to imagine future developments that can avoid changes. Within a century, for example, two technological discontinuities could occur, along with a major shift in societal values and perhaps a change in the balance of geopolitical power. Thus there is a growing literature on alternative scenarios that map a wide range of future possibilities. The hope is that, by mapping alternative development scenarios, it will be possible to identify a wider range of differing courses of action. These alternative scenarios are tools for capturing different relationships and the evolution of factors that determine future energy trajectories and spatial patterns.

It is important to realise that such approaches depend on assessments of

the driving forces of energy futures and the relationships among them, ranging from population developments to technological change. Usually a very small subset of alternative scenarios can be identified that will lead to sustainability. The driving forces in these scenarios must be consistent with the concept of sustainability. For example, such scenarios should not have dangerously high environmental impacts or inequitable resource allocation.

Such approaches also allow for the unfolding of different futures. Differing scenarios, while sharing similar outcomes, might have varying mixes of the same characteristics. For example, different economic development paths might lead to similar global energy requirements by the middle of the 21st century. A world with high population and relatively low levels of development might have almost the same total energy needs as a world with low population and high levels of affluence. But the latter clearly would offer more possible choices for achieving sustainability.

Energy scenarios for sustainable development

To assess what kinds of development will ultimately be sustainable, one must have a global perspective and a very long time horizon covering periods of at least a century. Chapters 1-4 amply illustrate that access to affordable energy services is a crucial prerequisite for sustainable development. At the same time, energy use is also a main cause of

environmental degradation at all scales and thus can impede achieving sustainability. (Often a higher degree of equity in the world is also included in the concept of sustainable development.)

Sustainable development is an elusive concept. It is often easier to define those development paths that are not sustainable than those that are. In many ways, this is the advantage of the concept. It has sufficient clarity to identify which development paths do not lead to a sustainable future, and it offers flexibility while being prescriptive. Sustainable energy scenarios are often designed to offer policy guidance on managing, for example, an orderly transition from today's energy system, which relies largely on fossil fuels, towards an energy system more compatible with sustainable development in all its dimensions (Goldemberg and others, 1988).[1]

Sustainable futures usually are not considered to be achievable with current policies and prevailing development trends.

All sustainable futures are in some sense positive and have some normative elements. In all of them the world develops equitably with relatively low environmental impacts. Sustainable energy scenarios

sometimes include strong assumptions about desirable futures; because they prescribe how such futures can be achieved, they are normative. In such normative approaches, sustainable futures usually are not considered to be achievable with current policies and prevailing development trends, but rather often depend on a fundamental change or a major paradigm shift.

Brief review of the literature on energy scenarios

The construction of scenarios to investigate alternative future developments under a set of assumed conditions dates far back in history. Scenarios were and continue to be one of the main tools for dealing with the complexity and uncertainty of future challenges.

The first scenarios were probably used to plan military operations. Scenarios now are being increasingly used in business enterprises and for many other commercial purposes. Perhaps most famous in the literature is the use of scenarios by the Shell Group in the wake of the so-called oil crisis to plan its corporate response strategies (Schwartz, 1991). Today scenarios are quite widespread and are found in all kinds of enterprises around the world. Many are quantitative; this is often the case for enterprises in the energy sector. Some of them also include considerations of sustainability. Recently the World Business Council for Sustainable Development presented a set of scenarios that was developed in

collaboration with 35 major corporations (WBCSD, 1998).

During the past 30 years a number of global studies have used scenarios as a tool to assess future paths of energy system development. One of the first global studies to employ scenarios for this purpose was conducted by IIASA during the late 1970s (Hfele, 1981). Another influential series of scenarios that included the assessment of sustainable development was formulated by the World Energy Council (WEC, 1993). The Intergovernmental Panel on Climate Change (IPCC) has used scenarios since its inception to assess greenhouse gas emissions and climate change. In 1992 it developed a set of very influential scenarios that gave a detailed treatment of energy sector developments. The set includes six scenarios called IS92, three of which describe futures that include characteristics of sustainable development (Pepper and others, 1992; Leggett, Pepper, and Swart, 1992).

A growing number of global studies consider futures with radical policy and behavioural changes to achieve sustainable development (Goldemberg and others, 1988). One of the first global scenarios to focus on achieving sustainable development was formulated by Greenpeace (Lazarus and others, 1993). Another among the first global energy scenarios with characteristics of sustainable development describes a transition to renewable energy futures (Johansson and others, 1993). In its second assessment report, the IPCC also considered a range of global energy

scenarios, based on some elements of the IS92 set, with varying degrees of sustainability (Ishitani and others, 1996).

In more recent studies, sustainable development scenarios are usually included among other alternative futures. This class of sustainable scenarios can be characterised by low environmental impacts at all scales and more equitable allocation of resources and wealth relative to current situations. Recently the Global Scenario Group presented a set of three scenarios that received considerable attention (Raskin and others, 1998). These scenarios were based on elaborate narratives describing alternative futures, including some that are decisively sustainable. The set of scenarios developed by the WBCSD also includes narratives and describes alternative development paths, some of which include strong emphasis on sustainable development (WBCSD, 1998).

There is also a large literature of global energy scenarios that serve as a reference for showing that, under business-as-usual conditions, many of the developments crucial for the achievement of sustainability would not be realised. For example, the *World Energy Outlook,* regularly published by the International Energy Agency (IEA, 1998), is very influential. Many of these global energy scenarios are limited to developments during the next 20-30 years and do not go far enough into the future to assess all crucial aspects of sustainable development, such as climate change. But they often are very relevant to issues such as the conditions for meeting the carbon

emissions targets specified in the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC, 1992).

The literature on sustainable energy scenarios is large, and this brief review cannot give a comprehensive account. The IPCC has developed a database that includes a number of global energy scenarios that can be characterised as describing sustainable development (Morita and Lee, 1998). This database, which includes more than 400 global and regional scenarios, illustrates that the literature is quite rich; thus not all scenarios can be described in this chapter. (In the following sections dealing with such scenario driving forces as economic development, some of the comparisons use scenarios from the database.)

The IPCC, in its recent *Special Report on Emissions Scenarios,* considers 40 scenarios that include a large number of sustainable futures (Nakicenovic and others, 2000). This set of scenarios is unique in a number of respects - it was developed using six different models, it covers a wide range of alternative futures based on the scenarios in the literature, it includes narrative descriptions of alternative futures, and it has been reviewed extensively.

Here some of the conditions for achieving a transition towards sustainable development will be illustrated with the three scenarios developed by IIASA and WEC. These will then be contrasted to a reference case that

captures many positive future developments but cannot be characterised as leading to sustainability. These scenarios cover a wide range of possible future developments and are representative of the scenario literature. Where appropriate, other scenarios will be drawn upon to illustrate the conditions and implications of sustainable development.

Three energy scenarios for the 21st century

IIASA and WEC undertook a five-year joint study published as *Global Energy Perspectives* (Nakicenovic, Grbler, and McDonald, 1998). The objectives of the study were to integrate near-term strategies through 2020 with long-term opportunities to 2100; analyse alternative future developments; ensure consistency and reproducibility with a unified methodological framework using formal models and databases; incorporate a dynamic treatment of technological change; and harmonise regional aspirations with global possibilities. The study centres on three cases of future social, economic, and technological development for 11 world regions.

The three cases unfold into six scenarios of energy system alternatives. Together they span a wider range of alternative future developments and driving forces. The three cases are designated as A, B, and C. Case A includes three variant scenarios and reflects a high-growth future of vigorous economic development and rapid technological improvements.

One of its variants (A3) includes many characteristics of sustainable and equitable development. Case B represents a middle course, with intermediate economic growth and more modest technological improvements. Case C is ecologically driven (with two variants: C1, with new renewables and a phaseout of nuclear energy by 2100; and C2, with renewables and new nuclear); it incorporates challenging environmental and energy taxes to simultaneously protect the environment and transfer wealth from North to South to enhance economic equity. This approach leads to lower energy use but high overall growth, especially in the South. Case C illustrates most vividly the conditions for achieving a high degree of sustainability and equity in the world. Table 9.1 gives an overview of the three cases and their six scenarios of energy development. Full documentation is available in the published study report (Nakicenovic, Grbler, and McDonald, 1998) and at the study Website (http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py).

These scenarios received a wide review that included about 100 leading energy experts. They incorporate both a top-down approach based on an integrated set of energy, economic, and environmental models to initially develop the set of scenarios, and a bottom-up evaluation of the regional perspectives provided by the 11 review groups. This set of scenarios will be used to illustrate to what extent the concepts of sustainable development are captured across the scenarios. They have been chosen because they cover a wide range of alternative future developments and

are quite representative of the recent scenario literature. Again, where appropriate, reference will be given to other scenarios from the literature.

Three of the six scenarios will be used to illustrate alternative conditions for achieving transitions of energy systems towards sustainability. Table 9.2 provides a number of indicators that may be used to characterise the achievement of sustainable development in energy scenarios and shows how the three scenarios selected for this assessment fare in comparison with each other. The middle-course scenario (B) was chosen to serve as a reference baseline because it was designed to represent a future characterised by incremental and gradual changes. In fact, this scenario would represent a major improvement in the global energy system and its use, but it does fall short of fulfilling many indicators of the sustainability suggested in table 9.2. The other two scenarios shown in table 9.2 (A3 and C1) describe futures that include characteristics of sustainability. The third scenario (C2), which can also be characterised along the same lines, includes continuous reliance on nuclear energy, in contrast to the other ecologically driven scenario, which has a global nuclear phaseout by 2100 (C1). Neither the A3 nor the C1 scenario, however, is compatible with current trends and developments, so both would require new policy initiatives and measures directed towards achieving sustainable development. Even so, neither of the scenarios ranks very high on all 13 indicators of sustainability considered in table 9.2. At the same time, table 9.2 indicates that, among the spectrum of energy futures considered here,

C1 represents the energy future that is the most compatible with sustainable development.

TABLE 9.1. SUMMARY OF THREE ENERGY DEVELOPMENT CASES IN 2050 AND 2100 COMPARED WITH 1990

		Case A High growth	Case B Middle growth	Case C Ecologically driven
Population (billions)	1990	5.3	5.3	5.3
	2050	10.1	10.1	10.1
	2100	11.7	11.7	11.7
Gross world product (trillions of 1990 dollars)	1990	20	20	20
	2050	100	75	75
	2100	300	200	220
Gross world product (annual percentage change)	1990-2050	**High**	**Medium**	**Medium**
	1990-2100	2.7	2.2	2.2
		2.5	2.1	2.2
Primary energy intensity	1990	19.0	19.0	19.0

(megajoules per 1990 dollar of gross world product)				
	2050	10.4	11.2	8.0
	2100	6.1	7.3	4.0
Primary energy intensity improvement rate (annual percentage change)	1990-2050	**Medium**	**Low**	**High**
	1990-2100	-0.9	-0.8	-1.4
		-1.0	-0.8	-1.4
Primary energy consumption (exajoules)	1990	379	379	379
	2050	1,041	837	601
	2100	1,859	1,464	880
Cumulative primary energy consumption, 1990-2100 (thousands of exajoules)	Coal	8.9 - 30.7	17.5	7.1 - 7.2
	Oil	27.6 - 15.7	15.3	10.9
	Natural gas	18.4 - 28.7	15.8	12.2 - 12.9
	Nuclear	6.2 -	10.5	2.1 - 6.2

	energy	11.2		
	Hydropower	3.7 - 4.2	3.6	3.6 - 4.0
	Biomass	7.4 - 14.3	8.3	9.1 -10.1
	Solar energy	1.8 - 7.7	1.9	6.3 - 7.4
	Other	3.0 - 4.7	4.3	1.4 - 2.2
	Global total	94.0 - 94.9	77.2	56.9
Energy technology cost reductions (through learning)	Fossil	**High**	**Medium**	**Low**
	Non-fossil	**High**	**Medium**	**High**
Energy technology diffusion rates	Fossil	**High**	**Medium**	**Medium**
	Non-fossil	**High**	**Medium**	**High**
Environmental taxes (excluding carbon dioxide taxes)		**No**	**No**	**Yes**
Sulphur dioxide emissions (millions of tonnes of sulphur)	1990	58.6	58.6	58.6
	2050	44.8 -	54.9	22.1

		64.2		
	2100	9.3 - 55.4	58.3	7.1
Carbon dioxide emission constraints and taxes		**No**	**No**	**Yes**
Net carbon dioxide emissions (gigatonnes of carbon)	1990	6	6	6
	2050	9 - 15	10	5
	2100	6 - 20	11	2
Cumulative carbon dioxide emissions (gigatonnes of carbon)	1990-2100	910 - 1,450	1,000	540
Carbon dioxide concentrations (parts per million by volume)	1990	358	358	358
	2050	460 - 510	470	430
	2100	530 - 730	590	430
Carbon intensity (grams of carbon per 1990 dollar of gross world product)	1990	280	280	280
	2050	90 - 140	130	70

	2100	20 - 60	60	10
Investments in energy supply sector (trillions of 1990 dollars)	1990-2020	15.7	12.4	9.4
	2020-50	24.7	22.3	14.1
	2050-2100	93.7	82.3	43.3
Number of scenarios		**3**	**1**	**2**

The three cases unfold into six scenarios of energy system alternatives: three case A scenarios (A1, ample oil and gas; A2, return to coal; and A3, non-fossil future), a single case B scenario (middle course), and two case C scenarios (C1, new renewables; and C2, renewables and new nuclear). Some of the scenario characteristics, such as cumulative energy consumption, cumulative carbon dioxide emissions, and decarbonisation, are shown as ranges for the three case A and two C scenarios.

Source: Nakicenovic, Grbler, and McDonald, 1998.

Scenario A3 envisions a future with impressive technological improvements and subsequent high degrees of economic development, a structural shift first towards natural gas and then towards renewable and nuclear energy options, and very high levels of energy efficiency. Environmental impacts are therefore quite low in this future. Equity is

achieved through rapid development, with today's developing regions achieving a high level of affluence by the end of the 21st century. The development gap narrows, increasing equity in the world. This scenario also includes characteristics of sustainability. This is achieved primarily through vigorous development (without active redistribution of income). Rapid technological and economic development allows access to an ever-expanding resource base with decreasing energy and material intensities, and a radical decline in adverse environmental impacts. However, it requires a paradigm shift and a host of new policies.

The ecologically driven case C scenario presents a rich and 'green' future and represents a fundamentally different development path. It includes both substantial technological progress and unprecedented international cooperation centred explicitly on environmental protection and international equity - it includes a high degree of environmental protection at all scales, from indoor air pollution to climate, with active redistribution of wealth and very high levels of energy efficiency and conservation. It fulfils most of the other criteria associated with sustainable development (see table 9.2), such as increasing equity, both in an economic and ecological sense, among regions and countries. Thus it can be considered to lead to sustainable development. For example, it incorporates a challenging, broad portfolio of environmental control technologies and policies, such as emissions standards and caps, incentives to encourage energy producers and consumers to use energy more efficiently and

carefully, 'green' taxes (levied on energy and carbon), international environmental and economic agreements, and technology transfer.

TABLE 9.2. CHARACTERISTICS OF SUSTAINABILITY IN THREE ENERGY DEVELOPMENT SCENARIOS IN 2050 AND 2100 COMPARED WITH 1990

Indicator of sustainability	1990	Scenario A3	Scenario B	Scenario C1
Eradicating poverty	Low	Very high	Medium	Very high
Reducing relative income gaps	Low	High	Medium	Very high
Providing universal access to energy	Low	Very high	High	Very high
Increasing affordability of energy	Low	High	Medium	Very high
Reducing adverse health impacts	Medium	Very high	High	Very high
Reducing air pollution	Medium	Very high	High	Very high
Limiting long-lived radionuclides	Medium	Very low	Very low	High
Limiting toxic materials[a]	Medium	High	Low	High
Limiting GHG emissions	Low	High	Low	Very high
Raising indigenous energy use	Medium	High	Low	Very high
Improving supply efficiency	Medium	Very high	High	Very high
Increasing end-use efficiency	Low	High	Medium	Very high

Accelerating technology diffusion	Low	Very high	Medium	Medium

a. For this row only, the qualitative indicators are not based on quantitative features of the scenarios, but were specified by the authors on the basis of additional assumptions.

The case C scenario also reflects substantial resource transfers from industrialised to developing countries to spur growth and eradicate poverty. These transfers include stringent international environmental taxes and incentives, which recycle funds from industrialised countries (members of the Organisation for Economic Co-operation and Development, or OECD) to developing countries. Specifically, it is assumed that energy and carbon taxes are applied universally, albeit at different rates and timing, and that the tax revenues are used to promote development. In the scenario, this means that the proceeds from these taxes in OECD countries are recycled as resource transfers to developing countries and are earmarked for the development of energy infrastructure, clean technologies, efficiency, and conservation. Because this scenario requires a fundamental paradigm shift from current socioeconomic, technological, and environmental development trends, new policies would be required to achieve the future it describes. Thus the transition towards more sustainable development paths in both cases C and A3 would require a host of new policies to promote the diffusion of advanced technologies, reliable and affordable access to energy for all, free trade, vigorous

economic growth, and reduced emissions at all scales. These findings are consistent with chapter 12, where it is stated that new policies would be required to achieve more sustainable development.

The three cases have a number of common features. All provide for substantial social and economic development, particularly in the developing world, and all give much wider access to reliable, affordable energy throughout the world. During the 21st century, as affluence increases throughout the world, the current distinction between developing and industrialised regions will become less and less appropriate in the scenarios considered here. All the scenarios provide for improved energy efficiencies and environmental compatibility, and hence for associated growth in both the quantity and quality of energy services.

BOX 9.1. DEMOGRAPHIC TRANSITION AND POPULATION GROWTH

Population is one of the driving forces of future energy requirements. Today there are three main sources of global population projections: the United Nations (UN, 1998), World Bank (Bos and Vu, 1994), and IIASA (Lutz, Sanderson, and Scherbov, 1997).

Most central population projections lead to a doubling of global population by 2100, to about 10 billion, compared with 5.3 billion in 1990. In recent years the central population projections for 2100 have declined somewhat but are still in line with a doubling by 2100. For example, the latest UN (1998) medium-low and medium-high projections indicate a range of between 7.2 and 14.6 billion people by 2100, with the medium scenario at 10.4 billion. The IIASA central estimate for 2100 is also 10.4 billion, with 95 percent probability that world population would exceed 6 billion and be lower than 17 billion (Lutz, Sanderson, and Scherbov, 1997).

Thus the population assumptions in the IIASA-WEC scenarios are higher (11.7 billion in comparison with 10.4 billion) but still consistent with recent population projections (see figure 9.3). It should be noted that the population projections used in most scenarios that describe sustainable development paths appear to have the same range as for all other scenarios in the literature. This implies that population policies are apparently not considered appropriate for achieving sustainability, nor is energy seen as an appropriate instrument for achieving the population transition, at least across most of the scenarios in the literature (see chapter 2).

The task is indeed daunting. Nearly 2 billion people, or a third of the world's population, lack access to adequate, affordable, clean, and convenient energy services such as electricity (chapter 2). The current disparities in energy use mirror the disparities in access to affordable energy services and in the distribution of wealth - the richest 20 percent of the world's population uses 55 percent of final, primary energy, while the poorest 20 percent uses only 5 percent. Exclusion from modern energy

services is generally associated with poverty and environmental degradation.

Although it is true that about two-thirds of the global population, or about 4 billion people, are now connected to electricity and that great progress has been achieved, the challenge ahead is formidable; a simple calculation illustrates its magnitude. In addition to the 2 billion people today who still need to be connected to energy distribution or decentralised systems and endowed with sufficient purchasing power to be able to afford modern energy services, two to three times as many people are likely to be added to the global population during the new century. This means that 6-8 billion people would need to be provided with the access to affordable, clean, flexible, and convenient energy services during the 21st century, a number larger than the current world population. All scenarios considered here achieve this transition - to a varying extent and through different energy system developments. Some of them do so while fulfilling some of the criteria of sustainable development as well (see the conclusion to this chapter).

In all three cases the structure of final energy develops towards greater flexibility, quality, and environmental compatibility, and energy intensities improve steadily. To facilitate comparisons among the three cases, all share the same central demographic baseline assumption, in which global population grows to 10 billion people by 2050 and to nearly 11.7 billion by

2100. This is higher than the current medium projections of about 10.4 billion in 2100 by the World Bank, United Nations, and IIASA (box 9.1). This means that 6-8 billion additional people would achieve access to adequate energy services in all three cases.

Economic development and equity

Economic development and growth are fundamental prerequisites for achieving an increase in living standards and equity in the world. It is therefore not surprising that assumptions about economic development are among the most important determinants of energy scenarios. At the same time, economic growth prospects are among the most uncertain determinants of scenarios.

Economic and social development has many dimensions, and a number of indicators have been devised to assess progress and setbacks in human development. The United Nations Development Programme defines development as the furthering of human choices (UNDP, 1997). Arguably, choices are only possible once basic human needs for food, shelter, health care, and education have been met. Eradication of poverty is essential for achieving sustainability and human development in general. Beyond the satisfaction of basic needs, the issue of what constitutes development involves many cultural, social, and economic factors that inherently involve questions of values, preferences, and policies.

Income is not an end in itself, but rather a means of enabling human choices - or foreclosing them, in the case of poverty. Therefore per capita income (usually measured by per capita GDP) has been widely used to indicate the degree of economic development. In many instances this is closely correlated (as lead or lag indicator) with other indicators and dimensions of social development, such as mortality, nutrition, and access to basic services.

Although future rates of economic development are highly uncertain, in all three cases of economic development considered in the IIASA-WEC study, future economic and energy markets move to today's developing countries. The rate and timing of this transition varies across the three cases, but the overall direction of change is the same. Along with population growth, the economic catch-up of developing to industrialised countries implies a long-term shift in the geographic focus of economic activities.

Currently the situation is fundamentally different. OECD countries produce and consume close to 80 percent of global economic output (measured by gross world product), while they account for less than 20 percent of global population. These disparities are illustrated in figure 9.1, which shows the size of 11 world regions in proportion to their 1990 GDP (at market exchange rates and 1990 prices). In 1990 the economic map of the world was very different from geographic maps (Mercartor projections) - it was highly distorted as a result of disparities among regions. Most developing

regions were barely discernible relative to Japan, Western Europe, and North America. In figure 9.1, for example, compare the size of Japan in 1990 with that of China or the Indian subcontinent.

For 2050 and 2100, the economic maps shown in figure 9.1 correspond to case B, the middle-course scenario of the IIASA-WEC study that is the most cautious with respect to the speed of the developing world's economic catch-up. Nonetheless, over the long term economic maps begin to resemble the geographic maps with which all of us are familiar. This means two things. First, economic catch-up, even in relative terms, is a century-long process and one of the greatest human challenges. Some regions may forge ahead, but in the aggregate developing countries will require more than 50 years to approach the income levels that OECD countries had in the 1960s or 1970s. Second, with long-term development and catch-up (in relative but not absolute terms), economic, as well as energy market, growth will be primarily in the developing world.

In figure 9.1, between 1990 and 2100 the world economy increases in size 10 times, from $20 trillion to $200 trillion (1990 dollars; or $24 trillion to $240 trillion in 1998 dollars). This leads to more equitable distribution of economic activities geographically, but the gap in per capita income remains very large. Therefore, in this scenario, in many parts of the world local difficulties will persist and, despite rapid economic development, adequate energy services may not be available to every citizen even 100

years from now. Higher rates of economic development are required to narrow the gap more substantially.

The richest 20 percent of the world's population uses 55 percent of final, primary energy, while the poorest 20 percent uses only 5 percent.

This is illustrated in table 9.3, which compares per capita income for the three cases (A, B, and C) for the 11 world regions. Cases A and C include the three more sustainable scenarios (A3, C1, and C2). The table shows that in case B only half of today's developing regions will achieve the 1990 income levels of OECD countries by 2100, whereas this is the case for most of the regions in the other three scenarios (A3, C1, and C2). The attainment of this higher degree of economic catch-up is, however, fundamentally different for the three more sustainable scenarios. In A3 this is achieved primarily through economic growth that results from liberalised markets, free trade, and high investment rates, whereas in C1 and C2 it is achieved through a substantial redistribution of wealth (from industrialised to developing countries and possibly from rich to poor) with a strong focus on maintaining environmental enmities. All three futures are more equitable than reference case B, leading to much higher economic development in the world. Gross world product increases by a factor of 11-

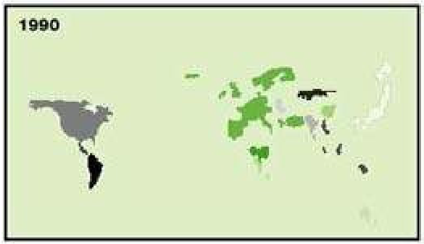
15 in A3, C1, and C2, to $220-300 trillion (1990 dollars; $270-370 trillion in 1998 dollars) by 2100.

A comparison of these three cases of economic development shows considerable uncertainty about future per capita GDP growth rates and about the effectiveness of different policy measures in reducing the relative income gap between today's industrialised and developing countries. The range across the scenarios is consistent with earlier reviews of economic growth assumptions for long-term scenarios by Nordhaus and Yohe (1983), Grbler (1994), Manne and Richels (1994), and Alcamo and others (1995). For instance, in the scenarios reviewed in Alcamo and others (1995), and Grbler (1994), per capita annual GDP growth rates typically are 1-3 percent for 1990-2100. On the basis of an average per capita income of $4,000 in 1990, global per capita GDP could range from $10,000-100,000 by 2100. Such uncertainties become amplified by regional disparities, in particular future productivity growth in developing countries.

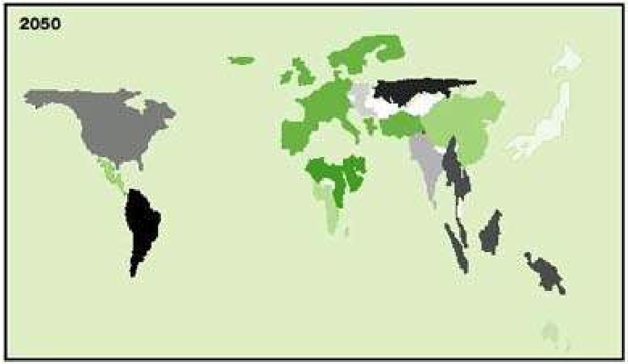
The great inherent uncertainty of future economic development prospects is reflected in the wide range of economic development paths assumed in the scenarios from the literature. The further one looks into the future, the higher is the uncertainty. By 2100 the range is between 3 (IS92c scenario, Pepper and others, 1992) and 30 times (FUND/EMF, modeller's choice scenario, Tol, 1995) the 1990 level (Nakicenovic, Victor, and Morita, 1998).

Thus the scenarios give a range of $60-$700 trillion, with a median of $240 trillion (1990 dollars; $290 trillion in 1998 dollars). These figures translate into an annual growth rate variation of 1.1-3.2 percent, and a median growth rate of 2.1 percent. Future economic growth rates therefore are generally assumed to be lower than those of historical experience.

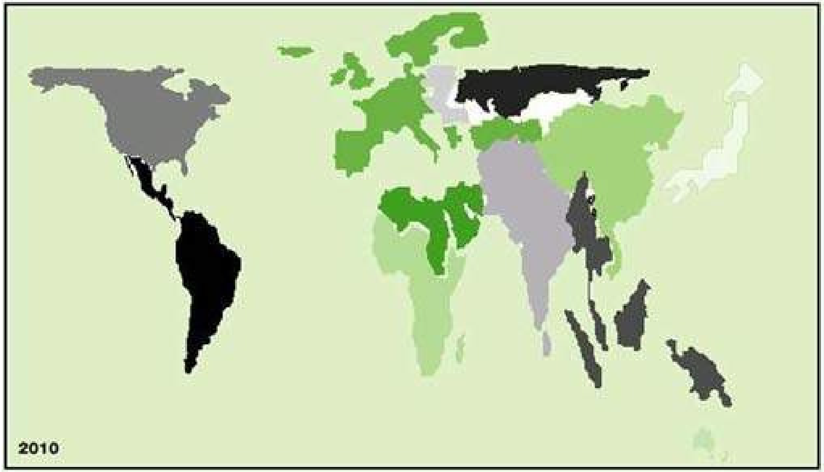
FIGURE 9.1. THE CHANGING GEOGRAPHY OF ECONOMIC WEALTH FOR THE MIDDLE-COURSE (CASE B) SCENARIO IN 2050 AND 2100 RELATIVE TO 1990



Figure



Figure



Figure

The areas of world regions are proportional to their 1990 levels of GDP, expressed at 1990 market exchange rates.

Source: Nakicenovic, Grbler, and McDonald, 1998.

It is important to note that by 2100 the global scenarios that represent sustainable development are mostly above the median of about $240 trillion (1990 dollars). Assuming a central population projection of 10 billion people by 2100, the median growth path translates into about $24,000 (1990 dollars; $29,000 in 1998 dollars) average per capita gross world product, or roughly the current per capita income level in more affluent industrialised countries. Thus economic growth rates are high for the scenarios that achieve sustainability, indicating that economic development is a prerequisite for both higher equity and lower environmental impacts. This tendency is also reflected in the three more sustainable scenarios in the IIASA-WEC study relative to the reference case.

Improvement of energy intensities

In all three cases economic development outpaces the increase in energy, leading to substantially reduced energy intensities. As technologies progress, and as inefficient technologies are replaced by more efficient ones, the amount of primary energy needed per unit of GDP - the energy

intensity - decreases. In some developing regions the intensity of commercial energy initially increases as traditional, less efficient forms are replaced by commercial energy, but total energy intensity decreases in these cases as well. All other factors being equal, the faster economic growth, the higher the turnover of capital and the greater the increase in energy intensity.

In the scenarios, improvements in individual technologies were varied across a range derived from historical trends and literature on future technology characteristics. When combined with the economic growth patterns of the different scenarios, the average annual overall global reduction in energy intensity varies from about 0.8 percent, in line with historical experience, to 1.4 percent. These figures bracket the long-term average annual rate for industrialised countries during the past 100 years of about 1 percent, and cumulatively lead to substantial energy intensity decreases across all scenarios (figure 4 in the overview). Efficiency improvements are significantly higher in some regions, especially for shorter periods of time.

These differences in global developments across the scenarios are reflected in even larger regional variations. The East Asian 'miracle' of double-digit average growth during the early 1990s has been interrupted recently, but prospects for continued sound growth are good for the coming decades. The transition economies of Central Asia, the Russian

Federation, and Eastern Europe have undergone a period of profound change and reform, reflected in a deep recession and economic decline during the 1990s. The prosperous economies of Western Europe have focused on reducing the high unemployment that accompanied low growth rates.

The IIASA-WEC scenarios start in the base year 1990 and were developed between 1992 and 1998, so that the actual trends of past years can be compared with initial developments in the long-term scenarios. Figure 9.2 shows the energy intensity improvement rates for six regions for the three cases of economic development relative to historical trends (figure 4 in the overview). They range from vigorous reduction of about 4 percent a year for China and other centrally planned economies in Asia to a (temporary) increase in energy intensities in the transition economies of Eastern Europe, Central Asia, and the former Soviet Union. The scenario trajectories provide an excellent anticipation of short-term developments during the 1990s, especially for the transition economies. All scenarios assume that the next few decades will be characterised by successful reform and restructuring in all transition economies, leading to sustained investment in the energy sector and economic development that will be reflected in long-term increases in energy intensities.

In addition to the energy intensity improvements, rates of technological change and available energy resources also vary consistently across the

scenarios. For example, high rates of economic growth are associated with rapid technological advance, ample resource availability, and high rates of energy intensity increase. Conversely low rates of economic growth result in a more limited expansion of energy resources, lower rates of technological innovation in general, and lower rates of decrease in energy intensities.

TABLE 9.3 PER CAPITA GDP FOR THE 11 WORLD REGIONS IN 1990 AND IN THE THREE IIASA-WEC CASES IN 2050 AND 2100 (THOUSANDS OF 1990 DOLLARS, MEASURED AT MARKET EXCHANGE RATES)

Region	1990	2050			2100		
		A	B	C	A	B	C
Sub-Saharan Africa	0.5	1.6	1.0	1.2	11.0	6.3	11.4
Centrally planned Asia and China	0.4	7.0	3.4	5.4	21.2	12.8	15.4
Central and Eastern Europe	2.4	16.3	7.8	8.0	52.7	29.0	21.8
Former Soviet Union	2.7	14.1	7.5	7.1	49.3	26.8	20.2
Latin America	2.5	8.3	7.1	7.4	27.8	20.1	21.0
Middle East and North Africa	2.1	5.6	4.0	4.1	13.8	11.0	12.9
North America	21.6	54.5	45.8	38.8	108.7	77.0	59.2
Pacific OECD	22.8	58.7	45.8	42.8	111.0	74.6	62.9

Other Pacific Asia	1.5	12.2	7.9	10.2	29.6	18.8	23.7
South Asia	0.3	2.0	1.3	1.8	15.3	10.0	14.8
Western Europe	16.2	45.9	37.1	32.9	93.5	63.9	53.7
World	**4.0**	**10.1**	**7.2**	**7.5**	**26.4**	**17.3**	**19.0**

Note: Three scenarios are shown; middle-course case B is compared with the three more sustainable scenarios, A3, C1, and C2, which are characterised by higher economic growth, greater equity, and substantially lower environmental impacts. All case A scenarios (A1, A2, and A3) share the same type of economic development, as do the case C scenarios (C1 and C2).

Source: Nakicenovic, Grubler, and McDonald, 1998.

Primary energy requirements and supply

Future rates of economic development are among the most important determinants of energy demand in the long term.[2] The IIASA-WEC study spans an increase in global energy needs in the range of 1.5-3 times by 2050, and 2-5 times by 2100. Taken together, energy requirements are envisaged to increase at lower rates than economic growth. This means that energy intensity is presumed to decline across all scenarios. By 2100 it falls to between 80 and 20 percent of 1990 levels. This translates into

annual declines of between 0.8 percent and more than 1.5 percent, with a median of about 1 percent. Thus the lowest future energy intensity improvements of 0.8 percent a year are in line with the historical experience of industrialised countries.

Figure 9.3 shows a wide range of alternative future primary energy requirements for the three scenarios. The energy needs for reference case B are in the middle, about tripling by 2100. This development is bracketed by the three more sustainable scenarios. A3 indicates substantially higher energy needs resulting from more rapid economic growth, despite much higher energy intensity. It nevertheless includes important characteristics of sustainability because it leads to a substantially higher degree of economic equity with lower environmental impacts at all scales. C1 (as well as C2) leads to the lowest energy requirements of all scenarios, to about a doubling by 2100, resulting from efficiency improvements and conservation; it is marked by a higher degree of economic equity and very low environmental impacts.

For comparison, figure 9.3 also shows the highest and lowest energy demand trajectories from the literature (Morita and Lee, 1998). The range of future energy requirements across the scenarios is indeed large, from a decline in the lowest scenario to an increase of 10 times in the highest. In absolute terms, the increase by 2100 in primary energy requirements - in comparison with 379 exajoules in 1990 - is expected to range from a

moderate increase, to 500 exajoules, to almost 3,200 exajoules. The highest energy requirements correspond to an annual growth rate of 2 percent, exactly in line with historical experience (since 1850; see figure 9.3). Also in line with historical experience, many scenarios project a growing demand for fossil energy, even if relative shares might be declining relative to alternative sources of energy. This again emphasises the need for continuing improvement in all energy efficiencies, including clean fossil fuels. The three IIASA-WEC scenarios cover a significant part of the full range of primary energy consumption spanned by other scenarios in the literature.

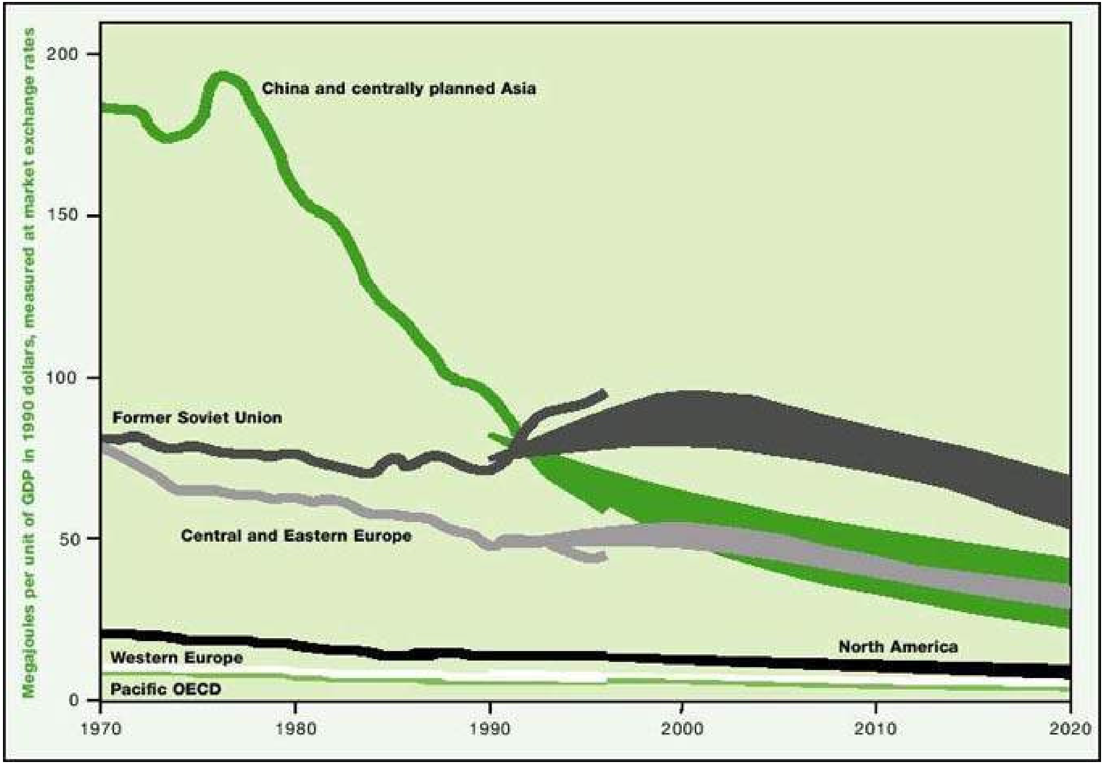


FIGURE 9.2. PRIMARY ENERGY INTENSITIES FOR 6 REPRESENTATIVE REGIONS OUT OF THE 11 WORLD REGIONS, 1970-96, AND IN THREE CASES, 1990-2020

Source: Nakicenovic, Grbler, and McDonald, 1998.

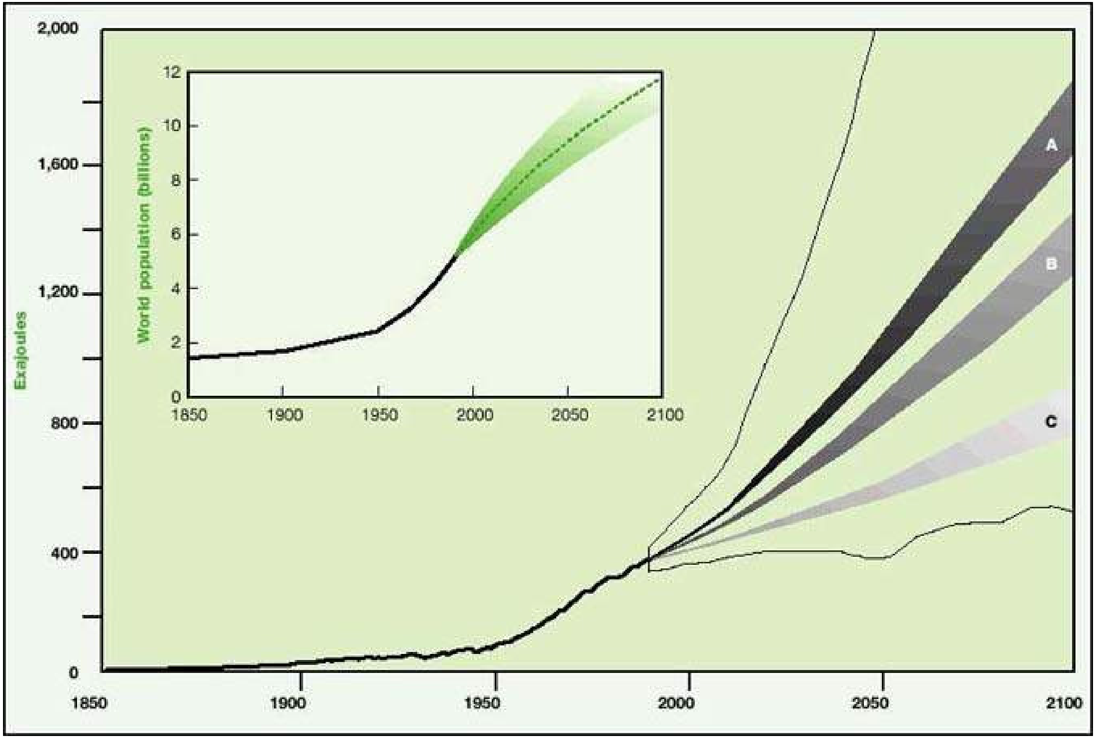


FIGURE 9.3 GLOBAL PRIMARY ENERGY REQUIREMENTS, 1850-1990, AND IN THREE CASES, 1990-2100

The figure also shows the wide range of future energy requirements for other scenarios in the literature. The vertical line that spans the scenario range in 1990 indicates the uncertainty across the

literature of base-year energy requirements. The insert shows global population growth, 1850-2000, and projections to 2100.

Source: Nakicenovic, Grbler, and McDonald, 1998; Morita and Lee, 1998; Nakicenovic, Victor, and Morita, 1998; Bos and Vu, 1994.

Finally, the inset in figure 9.3 shows the global population projections common to all IIASA-WEC scenarios. C1 leads to roughly constant per capita primary energy consumption during the 21st century and describes a transition towards more equity and lower environmental impacts. But it assumes implementation of challenging policies, such as world-wide energy and carbon taxes, that will change current development trends. In contrast A3 leads to a higher increase - by 2.5 times - in per capita energy requirements, but it shows that vigorous structural change of the energy system towards decarbonisation can lead to low environmental impacts, even in conjunction with very high levels of economic development and energy needs. The high rates of decarbonisation are, however, not sufficient to offset increased energy demand, so the total carbon emissions with A3 are substantially higher than those with C. Reference case B indicates energy needs in the median range relative to the other two alternatives (A and C) and the scenario literature in general, but it falls short of the transitions described in the other three more sustainable alternatives.

Alternative structures of future energy systems are capable of meeting this growing demand for higher-quality energy end use and services. Despite all the variations the scenarios look quite similar through 2020, and all still rely on fossil fuels. But after 2020 the scenarios diverge, and the energy transitions of the three more sustainable scenarios undergo a similar degree of structural change in the energy system.

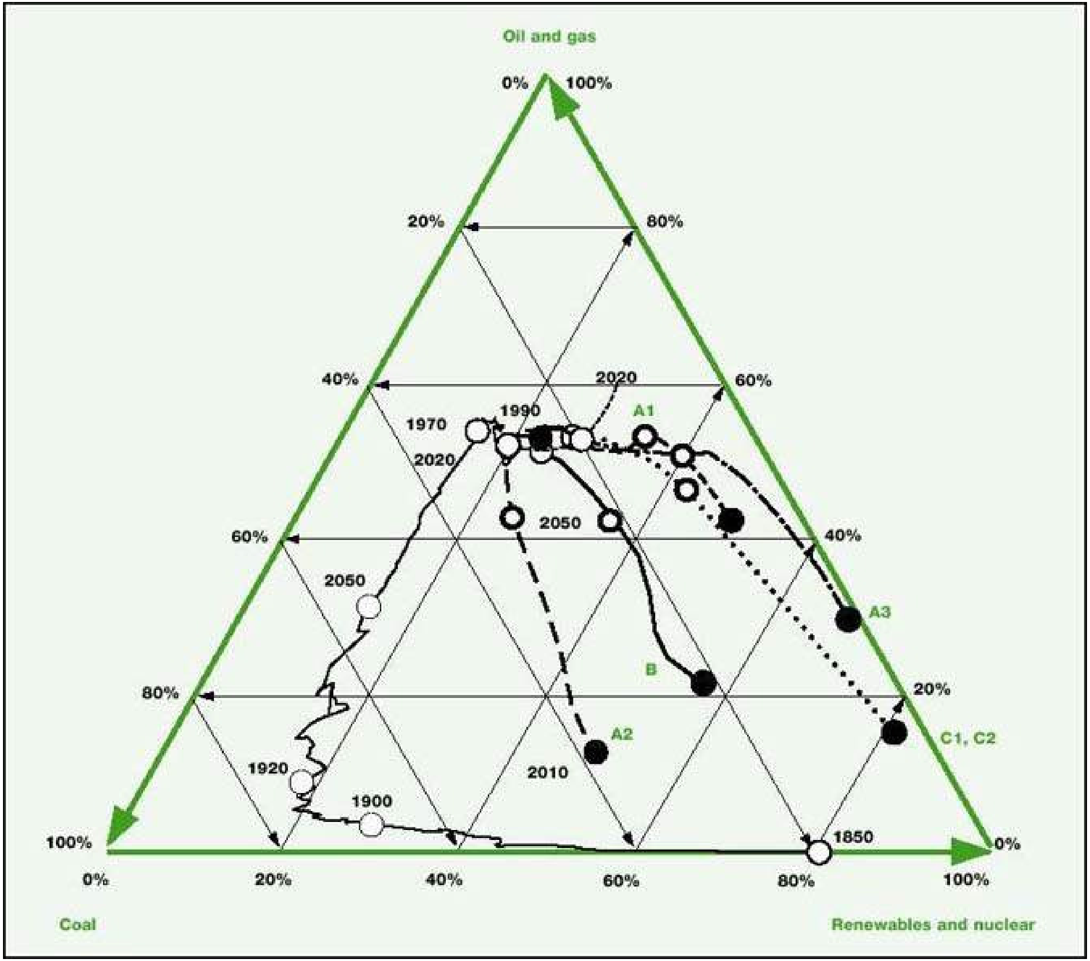

Oil and gas
0%
100%
20%
80%
40%
60%
2020
1990
A1
1970
2020
2050
2050
60%
40%
2050
A3
80%
B
20%
A2
C1, C2
1920
2010
1900
1850
100%
0%
0%
20%
40%
60%
80%
100%
Coal
Renewables and nuclear

FIGURE 9.4. EVOLUTION OF PRIMARY ENERGY STRUCTURE: SHARES OF OIL AND GAS, COAL, AND NON-FOSSIL SOURCES (RENEWABLES AND NUCLEAR), 1850-2000, AND IN SIX SCENARIOS, 2000-2100

Shares are measured against the grid lines with percentages shown on the three axes; see text for explanation of the figure.

Source: Nakicenovic, Grbler, and McDonald, 1998.

The roles of different primary energy sources, which vary across the six scenarios, contribute to this divergence. Some continue to be fossil fuel intensive; others envisage stronger shifts towards alternative sources such as renewables or nuclear power. The geophysical availability of energy resources is not a major constraint, even though currently estimated conventional oil and gas reserves would soon be depleted across most of the scenarios. Instead the availability of energy resources and the rates at which they are converted into reserves are a function of the envisaged development strategies in the scenarios. Part of the divergence in the structures of energy systems depends on policy choices and development strategies. For example, the two case C scenarios that assume strong international cooperation focused on environmental protection through energy and carbon taxes rely much less on fossil fuel than do the other scenarios. Figure 9.4 illustrates this long-term divergence in the structures of energy systems across the scenarios.

Each corner of the triangle in figure 9.4 represents a hypothetical situation in which all primary energy is supplied by a single energy source: oil and gas on the top, coal on the lower left, and renewables and nuclear energy on the lower right. Nuclear energy and renewables are grouped together because they are in principle the non-fossil energy alternatives available in the longer term. The illustration shows the historical development of the global energy system starting in the 1850s, when most primary energy needs were met by traditional (renewable) sources of energy, such as wood and animal power, which in some cases are still harnessed in an unsustainable manner - contributing to about 10 percent of deforestation and other adverse impacts (chapters 3, 5, and 7).

The first transition in the historical development of the global energy system, which lasted about 70 years, from 1850 to 1920, involved the substitution of coal for traditional energy sources. The share of traditional non-fossil energy sources declined from about 80 to 20 percent during this period, while the share of coal increased from 20 to more than 70 percent. The next transition has also lasted about 70 years, from 1920 to the present. It involves the substitution of oil and gas for coal. The share of coal has declined to about 30 percent, while the share of oil and gas has increased to about 50 percent.

Figure 9.4 illustrates alternative development paths in the structure of the energy system that might characterise the next transition. Scenarios

branch out after 2020. Some become coal intensive, such as reference case B and high-growth A2. Others are more renewable and nuclear intensive, such as the more sustainable A3 and ecologically driven C1 and C2. All the scenarios eventually lead to a partial shift from fossil fuels to other sources of energy; however, they follow alternative development paths. As the paths spread out, they form diverging future developments. To some extent they are mutually exclusive.

Most of the divergence after 2020 will depend on technological developments and industrial strategies implemented between now and then. Which energy sources in 2020 will best match the more flexible, more convenient, cleaner forms of energy desired by consumers? Which firms will have made the investments in research and development that will give them a technological edge? And which will have refocused their operations away from merely providing tonnes of coal or kilowatt-hours of electricity and towards offering better energy services to consumers?

The answers to these questions will be determined between now and 2020. Near-term investment decisions and efforts in technology research and development will determine which of the alternative development paths will dominate the post-2020 period. For example, the scenarios have the same assumptions about fossil and nuclear energy resources and renewable energy potentials (chapter 5). But their use differs across the scenarios, and these differences tend to be amplified after 2020. Because

of the long lifetimes of infrastructure, power plants, refineries, and other energy investments, there will not be a sufficiently large turnover of such facilities to reveal large differences in the scenarios before 2020. But the seeds of the post-2020 world will have been sown by then. Figure 9.4 illustrates that the achievement of a more sustainably structured energy system should be seen as a cumulative, evolutionary process: It needs to be initiated early to allow for the long time constants required for fundamental transitions, such as a shift to cleaner fossil fuels, renewables, and possibly nuclear energy.

The achievement of a more sustainably structured energy system needs to be initiated early to allow for the long time constants required for fundamental transitions to cleaner fuels.

Long-term global energy futures are no longer seen as being geologically preordained. The imminent resource scarcity forecast in the 1970s did not materialise. With continued exploration efforts and technological progress, accessible and affordable reserves have increased, and this trend is likely to continue. After 2020 all scenarios move away from their current reliance on conventional oil and gas. As mentioned, the currently estimated conventional oil and gas reserves do not reach much into the post-2020

periods in any of the scenarios (chapter 5). This transition progresses relatively slowly in scenario A1, where oil and gas are plentiful. In the more sustainable scenarios, A3, C1 and C2, it progresses more rapidly because of faster technological progress towards cleaner fossil energy systems (A3) or because energy and environmental policies favour non-fossil alternatives (C1 and C2).

An ecologically driven clean-fossil version of case C is also conceivable. Such a third C variant (C3) would incorporate most of the environmentally compatible fossil energy conversion system together with decarbonisation and carbon removal and storage. But such a scenario was not developed, for two reasons. First, A3 already includes clean and efficient fossil energy technologies, along with some carbon removal and its use for enhanced oil recovery. Thus limited carbon removal and sequestration occur for economic reasons and are competitive with other options for enhanced oil recovery. But additional carbon removal, although technically possible, is expensive and thus would require introducing carbon taxes or emissions limits. In A3 cumulative carbon emissions are about 1,000 gigatonnes for 1990-2100. Thus that amount of carbon - about 50 percent more than now in the atmosphere - would need to be stored. Disposal in geological reservoirs is possible; however, the amounts involved are gigantic, and affordable disposal and storage systems still need to be developed (chapter 8). Second, the advantage of an ecologically driven clean-fossil version of case C would basically be very similar to A3 but would have the

advantage of requiring storage of much less carbon, but still a very large amount, comparable to the current carbon dioxide in the atmosphere.

In scenario A2 and reference case B, the transition away from oil and gas includes an important contribution from coal, whose long-term market share after 2050 is 20-40 percent. Nonetheless little of this coal is used directly. Instead it is converted to high-quality energy carriers (electricity, liquids, and gases) demanded by high-income consumers after 2050. Thus very different resource and technological options can be drawn upon to meet the cleaner energy being demanded by more and more affluent consumers world-wide.

Technological dynamics and structural change

Technology is the key determinant of economic development and is essential for raising standards of living and for easing humanity's burden on the environment (Grbler, 1998b). Because technological progress is based on human ingenuity, it is thus a human-made resource that is renewable - as long as it is nurtured. But this nurture has a price. Innovation, especially the commercialisation of novel technologies and processes, requires continual investments of effort and money in research, development, and demonstration (RD&D). Technology diffusion, in turn, depends on both RD&D and learning by doing. Some advanced technologies important in the scenarios - such as hydrogen production,

distribution, and end use - would be radical innovations that are not likely to result from incremental improvement of current technologies. And without investment and experience, there can be no long-term technological improvement, either through incremental or radical change.

Innovation and technology diffusion require both that opportunities are perceived and that the entrepreneurial spirit exists to pursue them. Long-term scenarios cannot forecast future technological ‘winners’ or ‘losers’, but they can indicate areas of technological opportunity. Figure 9.5 illustrates the global market potential in the IIASA-WEC scenarios for four classes of energy technologies: new end-use energy devices (efficient lighting, heat pumps), power plants, synfuel production (from biomass, coal, and natural gas), and energy transport, transmission, and distribution infrastructure. For each of the four classes of technologies, the minimum, maximum, and average market potential for the six scenarios are shown in 2020, 2050, and 2100.

Across the wide variation in possible energy developments depicted in the scenarios, the importance of energy infrastructure grows persistently. Even in the sustainable, low-demand scenarios of case C (C1 and C2), energy infrastructure delivers at least 400 exajoules a year by 2050. By the end of the century it averages 800 exajoules a year across all scenarios, reaching close to 1,600 exajoules a year in the highest scenarios. The markets for power sector technologies also grow substantially, with a

wide spread between the maximum and minimum scenarios. By 2050 the annual range is 120-560 exajoules (energy delivered). Part of this spread is due to uncertainties about demand growth, but part arises from energy end-use innovations in the form of new, on-site decentralised electricity generation technologies, such as photovoltaics or fuel cells. The potential for decentralised systems in the long term outgrows that of the power sector. The most important customers for energy technologies would no longer be a limited number of utility managers but rather millions of energy consumers world-wide. Synfuels also emerge in the long term as a major technology market. An orderly transition away from conventional oil and gas translates into large technology markets for synliquids, syngas - and, in the long term, increasing shares of hydrogen produced from both fossil fuels (coal and natural gas) and renewables (biomass). By 2100 the global synfuels market could be at least 160 exajoules a year, comparable to the current global oil market.

Long-term scenarios cannot forecast future technological 'winners' or 'losers', but they can indicate areas of technological opportunities.

As noted above, technological progress has a price - it requires continual investment in RD&D. All the technological improvements in the scenarios

that are reflected in the expansion of all technology categories shown in figure 9.5 presume steady RD&D investment. Given the importance of strategic investment in RD&D, it is a cause for concern that energy-related RD&D expenditures are currently declining in most OECD countries. Evidently upfront RD&D expenditures are increasingly viewed as too expensive in markets where maximising short-term shareholder value takes precedence over longer-term socioeconomic development and environmental protection.

The important conclusion from this analysis of IIASA-WEC scenarios is that far-reaching technological improvements (chapters 6-8) are central to the transition towards sustainable development and thus need to be developed and disseminated throughout the energy system - including to decentralised systems and end users. Perhaps this is not surprising because end use is the least efficient part of the whole energy system. These possible developments have two important implications. First, they weaken the argument for extensive RD&D investment in large, sophisticated, 'lumpy', inflexible technologies such as fusion power and centralised solar thermal power plants. Improvements in end-use technologies, through which millions, rather than hundreds, of units are produced and used, are more amenable to standardisation, modularisation, and mass production, and hence to benefit from learning-curve effects (resulting in cost reductions and performance improvements). Second, institutional arrangements governing final energy use and supply are

critical. The deregulation, reregulation, and liberalisation of electricity markets can create incentives in this direction; service packages can be tailored to various consumer preferences, especially because traditional consumers can sell electricity back to the grid. But liberalisation could discourage long-term RD&D by emphasising short-term profits.

The structure of final energy requirements

In virtually all energy scenarios in the literature, economic growth outpaces the increase in energy consumption, leading to substantial reductions in energy intensities and efficiencies. This is to a large extent due to technological change and structural changes towards less materials-intensive, more knowledge-intensive activities. As individual technologies are developed and enter the marketplace, inefficient technologies are replaced by more efficient ones, and the structure of the energy-supply system and patterns of energy services change. These factors reduce the amount of primary energy needed per unit of final energy delivered to end users, as well as final energy per unit energy service. With all other factors being equal, the faster economic growth, the higher the rate of technological change, the higher the turnover of capital, and the greater the decline in energy intensity and improvement of energy efficiency. These long-term relationships between energy efficiency and economic development are reflected in the majority of scenarios in the literature and are consistent with historical experience across a range of

alternative development paths in different countries.

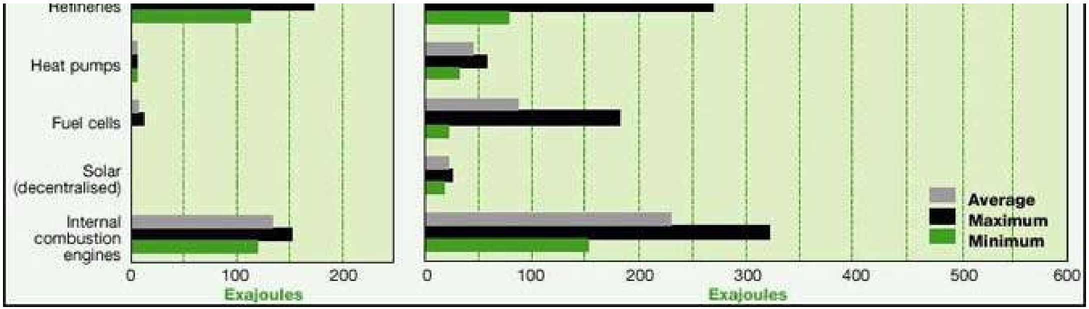


FIGURE 9.5. GLOBAL MARKET POTENTIALS FOR POWER PLANTS, SYNFUEL PRODUCTION, NEW END-USE ENERGY DEVICES, AND ENERGY INFRASTRUCTURE ACROSS SIX SCENARIOS, 2020 AND 2050

Source: Nakicenovic, Grbler, and McDonald, 1998.

The scenarios cover a wide range of energy supply possibilities to meet growing energy requirements, from a tremendous expansion of coal production to strict limits on it, from a phase-out of nuclear energy to a substantial increase in its use. Yet all the variations explored in the alternative scenarios match the continuing need for more flexible, more convenient, cleaner forms of energy. This means that all energy is increasingly converted into quality carriers such as electricity, liquids, and energy gases. For example, the direct end use of solids by final consumers disappears by 2050. Solid energy sources are more and more converted into liquids and gird-oriented energy carriers such as energy gases and

electricity.

Thus despite all the variations in major driving forces of energy end use across a wide range of scenarios, the pattern of final energy use is remarkably consistent across many scenarios that describe sustainable energy development. Figure 9.6 illustrates the convergence in the structure of final energy for the IIASA-WEC scenarios.

As shown in figure 9.6, all six scenarios portray a pervasive shift from energy being used in its original form, such as traditional direct uses of coal and biomass, to elaborate systems of energy conversion and delivery. This shift continues in all cases, leading to ever more sophisticated energy systems and higher-quality energy carriers. A second profound transformation is the increasing delivery of energy by dedicated transport infrastructure, such as pipelines and electric networks. This development enhances trade possibilities and promotes similar end-use patterns across regions with fundamentally different primary energy supply structures. Third, changes in final energy patterns reflect the changes in economic structure presented in the scenarios. As incomes increase, the share of transport, residential, and commercial applications also increases.

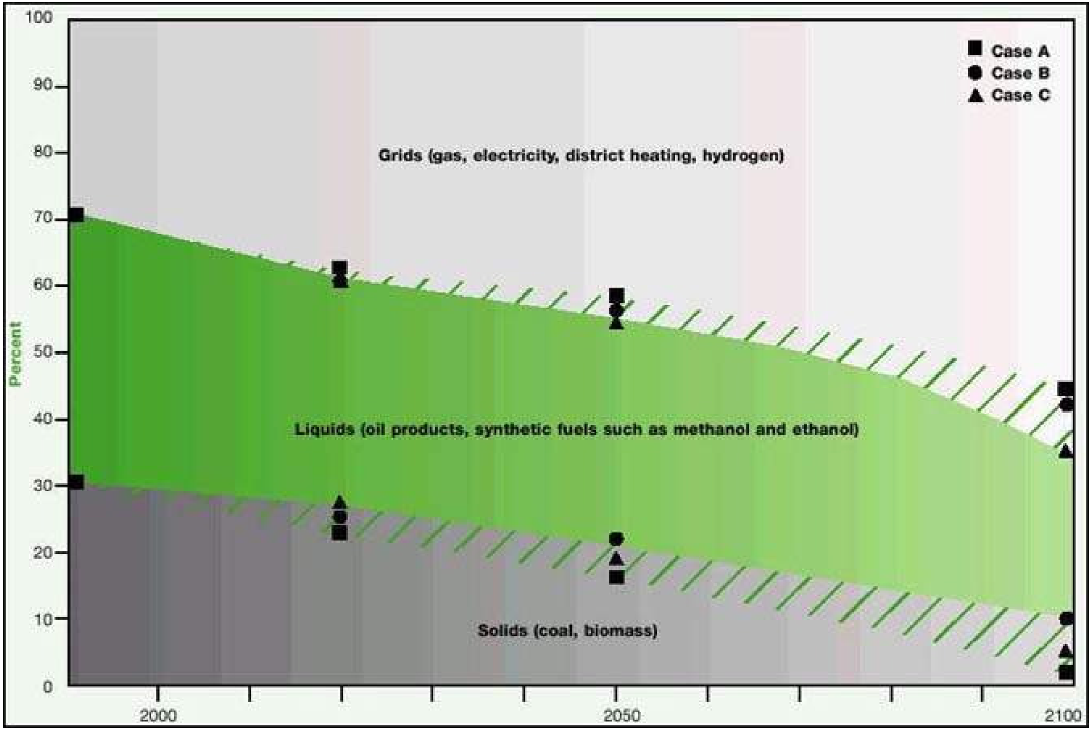


FIGURE 9.6 GLOBAL FINAL ENERGY SHARES BY FORM IN THREE CASES

Solids include direct delivery to end users. Overlapping areas indicate variations across the cases.

Source: Nakicenovic, Grbler, and McDonald, 1998.

These converging final energy patterns yield substantial quality improvements in the energy (and energy services) delivered to the consumer. Quality improvements are measured by two indicators: fuel-mix-induced efficiency gains and the carbon intensity of final energy. The efficiency of final energy use improves as the final energy carrier portfolio changes in the direction of higher-quality fuels. The effect is an improvement via inter-fuel substitution of 20-30 percent. The actual end-use efficiency gains are of course much larger, for they are mostly driven by technological change in end-use devices (cars, light bulbs, and so on). The main points are that more efficient end-use devices will require higher-quality fuels, and there is a high degree of congruence across all six scenarios. Thus whereas primary energy supply structures and resulting carbon intensities diverge in the IIASA-WEC scenarios, those of final energy converge. The decarbonisation trend of final energy relative to primary energy is also faster across all the cases.

These energy developments are characteristic of many sustainable scenarios. The use of non-commercial final energy generally disappears, while industrial and transport energy shares generally grow, largely due to an enormous increase in industrial production and mobility in developing countries. In industrialised regions, however, residential and commercial energy needs generally grow faster than those for industry. Growth of mobility, especially in developing regions, is one of the pervasive changes across all the scenarios. Even in industrialised countries, transport energy

requirements grow faster than any other final energy use. The share of final energy for transportation increases from one-fifth today to a third in the case A scenarios and to a quarter in the case C scenarios. The increase is more modest in C scenarios because of their orientation towards public rather than individual transport and towards partial replacement of mobility through communication. With high levels of affluence and leisure, new services and new activities emerge that shift final energy requirements away from materials- and energy-intensive production. The demographic changes associated with ageing and single-person households reinforce this trend in such scenarios.

As noted, some scenarios describe less-intensive mobility and urbanisation developments. This is true for the case C scenarios that foresee a stronger shift towards decentralised energy systems and reliance on local solutions. Final energy needs in the residential and commercial sector increase to more than half of all final energy after 2050. Mobility and materials-intensive production are replaced by communication and services, resulting in lower material and energy intensities. This leads to significant differences across regions and scenarios in the end-use devices that are used and in how they are used (that is, lifestyles), even when differences in total final energy demand are small. This points to an important but still poorly understood and thus weak interaction between lifestyles and energy services. An illustration is given in the IIASA-WEC study, which contrasts the three high-growth A scenarios for Latin America with the

ecologically driven C scenario for Western Europe. Both regions have a strong tradition of detailed analyses of energy end use and associated lifestyle changes (Goldemberg and others, 1988; Schipper and Meyers, 1992; IEA, 1993).

All six scenarios portray a pervasive shift from energy being used in its original form to elaborate systems of energy conversion and delivery.

Temporal and spatial scales of scenarios

Energy scenarios in the literature cover a wide range of time horizons, from 10-20 to more than 100 years. Sustainable energy scenarios usually have long time horizons. The inertia of energy systems is high, so it takes decades before a shift away from reliance on fossil energy sources can be achieved in sustainable scenarios. Major exceptions are some of the recent studies of policies and measures for meeting the carbon emission targets specified in the Kyoto Protocol (UNFCCC, 1992). The protocol calls for the reduction of emissions in industrialised countries (so-called Annex I under the UNFCCC) by about 5 percent relative to the base year 1990 during the 2008-12 period (UNFCCC, 1997). A number of scenarios in the literature (such as IEA, 1998) focus on this time period and on achieving emission

reductions. Some of these scenarios would presumably lead to sustainable development in the long run, assuming that structural change towards clean fossil and non-fossil energy continues.

Generally, however, most scenarios that describe sustainable development have long time horizons, usually extending for 100 years. They make up an important share of all long-term energy scenarios. They share a number of features with other long-term scenarios that are significantly different from those of short-term scenarios. In general the longer the time horizon, the lower the likely growth rates of driving forces and energy need. This tendency is probably linked to the fundamental difference between short- and long-term scenarios. Short-term scenarios are often national or regional and frequently describe energy options that may be overly optimistic from a global perspective. In contrast long-term scenarios are often global and focus on possibilities that might be more limited than regional expectations.

The variability and uncertainty of regional and global scenarios also tend to increase with higher temporal and spatial resolutions. Thus over longer periods and larger areas, developments tend to average out, leading to lower variations and uncertainties. If this is generally true, then it means that the future is more open at higher scales of spatial and temporal resolution, requiring a larger portfolio of alternative scenarios to cover the range of possibilities.

Spatial phenomena are therefore important for developing and interpreting scenarios. For example, many scenario environmental impacts require a detailed regional resolution. Many environmental phenomena require that scenario driving forces, energy use, and emissions be gridded with a very high spatial resolution. Very few scenarios and modelling approaches are based on a fine geographic scale. Thus, for a number of reasons, national or regional spatial scales are not always ideal for energy scenarios. But such scenarios are rare due to many unresolved methodological issues. With current methodological approaches, energy-related spatial phenomena are more difficult to capture on the global scale than evolution in time.

There are, of course, exceptions. Recent scenarios by Srensen, Kuemmel, and Meibom (1999) have high geographic resolution for driving forces as well as energy use patterns (box 9.2). The scenarios highlight the uneven geographic distribution of economic activities, resources, and energy patterns - and also bring new insights into energy trade implications, energy infrastructure, and transport. For example, the scenarios that rely on clean fossil fuel and safe nuclear energy options entail trade and transmission of energy in much the same pattern as today. This situation has important implications for economic development in energy-importing countries that may have lower economic growth relative to other scenarios with more self-sufficient domestic provision of energy. The scenarios demonstrate that focusing on decentralised, renewable energy sources

with low energy densities would make it difficult to match energy demand growth in some parts of the world by 2050. In contrast scenarios that also rely on centrally produced renewable energy create supply in excess of demand and through trade foster robust energy systems and low adverse environmental impacts (Srensen, Kuemmel, and Meibom, 1999).

The legacy of past generations

Energy scenarios explore the future and rarely look at the past. But the dynamics of history matter for future developments. This is especially relevant to scenarios that achieve sustainability for future generations. Equity often plays an important role in such considerations.

This is in stark contrast to our common history. Both in the past and today, a small minority of the global population accounts for most economic activity, materials use, and mobility, just to mention a few driving forces of energy use. Thus most energy is consumed by a relatively small, affluent part of the global population that lives in industrialised countries; this 20 percent of the population enjoys about 80 percent of gross world product (see figure 9.1) and more than 60 percent of global energy consumption. Historically, today's affluent part of the global population has consumed about 80 percent of fossil energy. Its many benefits from this consumption include enormous economic development. But many of the adverse environmental and other impacts of this cumulative energy consumption

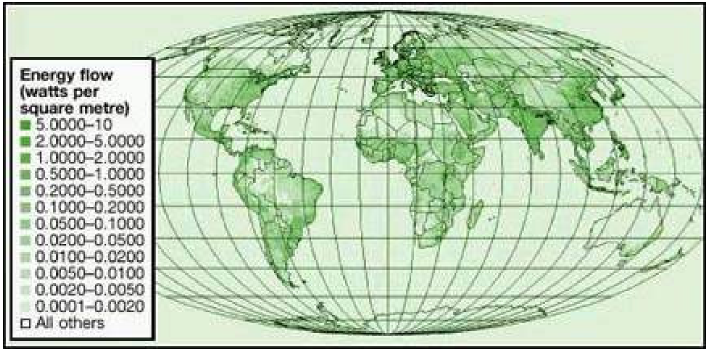
have been shared with the rest of the world.

Most sustainable energy scenarios envisage a fundamental change in the future from today's inequitable distribution of benefits and adverse impacts. The scenarios use various methods to implement policies to move global development towards sustainability. For example, the IIASA-WEC case C scenarios assume revenue-neutral energy and carbon dioxide taxes whose proceeds enhance international collaboration and resource transfers from industrialised to developing regions. This situation may appear unrealistic from the current perspective, but it was necessary to achieve both rapid development of poor regions and environmental protection. Another example is the so-called B1 family of sustainable scenarios (developed by different modelling approaches) for the IPCC *Special Report on Emissions Scenarios* (Nakicenovic and others, 2000) that all achieve equity through a host of policy and behavioural changes in the world, along with improvements of environmental compatibility at all scales (De Vries and others, 2000). Thus sustainable energy scenarios require challenging changes.

BOX 9.2. SPATIAL SCENARIO OF ENERGY END USE

Srensen, Kuemmel, and Meibom (1999) give an example of an energy scenario that emphasises demand-side management, high levels of energy efficiency, and conservation while attaining high levels of global prosperity. It assumes that average energy technology efficiency in 2050 will correspond to the best current rates. This results in total global energy end-use demand of about 220 exajoules in 2050. The scenario is thus characterised by relatively low energy requirements relative to the increase in per capita energy use. The energy available to the end user today is only about 12 percent of primary energy, and the challenge is to increase this fraction. The resulting energy requirements are roughly half those in the IIASA-WEC case C scenarios. Population assumptions are about the same. Srensen, Kuemmel, and Meibom (1999) base their scenario on UN median population projections (UN, 1996) and UN increasing urbanisation estimates (UN, 1997).

A unique feature of the scenario is a very high geographic resolution (using the middle scenario of UN, 1996), increasing urbanisation (UN, 1997), and an increase from today’s per capita energy use by an average factor of 2.7. GNP growth is larger because of the de-coupling of economic and energy growth, and the distribution of this growth across regions is not even (because a higher growth rate is assumed for today’s poor regions). Figure below shows the ‘gridded’ total energy delivered to end users in 2050.



Scenario of total energy delivered to end users, 2050

Note: Includes energy for air conditioning, process heat, stationary mechanical energy, electric energy, energy for transportation, and energy in food. The average energy demand is about 23 gigajoules per capita, or three times the amount made useful at the end use today.

Source: Srensen, Juemmel, and Meibom, 1999.

The role of policies

Sustainable energy scenarios usually assume or imply a host of measures to achieve their goals, from a transition from fossil energy sources to adoption of environmentally friendly behaviour patterns. The policies include market-based and regulatory mechanisms as well as assumed

changes in human behaviour (chapter 12). Regulatory standards, taxes, and emissions trading schemes are comparatively easy to implement in scenarios developed using formal models. But it is much more difficult to determine what measures would be required to achieve the behavioural and institutional changes called for in such scenarios. One example from recent IPCC scenarios is given here for illustrative purposes (Nakicenovic and others, 2000).

The IPCC B1 scenario family includes many characteristics of sustainable development. Its storyline or narrative description calls for extensive changes (for further details see the Website at http://sres.ciesin.org; http://www.ipcc.ch; http://www.iiasa.ac.at/Research/TNT/Draft/Publications/publications.html; De Vries and others, 2000; Nakicenovic and others, 2000; and Nakicenovic, 2000). The storyline assumes a high level of environmental consciousness and institutional effectiveness. Consequently environmental quality is high because most of the potentially negative environmental aspects of rapid development are anticipated and dealt with effectively at local, national, and international levels. For example, transboundary air pollution (acid rain) is basically eliminated in the long term. Land use is carefully managed to counteract the impacts of activities that could damage the environment. Cities are compact and designed for public and non-motorised transport, and suburban developments are tightly controlled. Strong incentives for low-input, low-impact agriculture, along with

maintenance of large areas of wilderness, contribute to high food prices with much lower levels of meat consumption.

These proactive local and regional environmental measures and policies also lead to relatively low energy requirements and low emissions, even in the absence of explicit interventions directed at conserving energy or mitigating climate change. The IPCC B1 world invests a large part of its gains in more efficient resource use (‘dematerialisation’), greater equity, stronger social institutions, and increased environmental protection. A strong welfare net prevents social exclusion on the basis of poverty. But the storyline also considers that counter-currents may develop, and in some places people may not conform to the main social and environmental intentions of the mainstream in this scenario family. Massive income redistribution and presumably high taxes may adversely affect the functioning of world markets. Environmental protection could become an issue in some parts of the world. This all illustrates how achieving sustainable development is a very difficult task - even in scenarios - as new policies play out in relation to other driving forces.

Most sustainable energy scenarios envisage a fundamental change in the future from today's inequitable distribution of benefits and adverse impacts.

Other examples of strong policies can be seen in nearly all sustainable development scenarios. The "Transformed World" of Hammond (1998), based on the "Great Transitions" of Gallopin and others (1997), stresses the role of global technological innovation in addition to enlightened corporate actions, government policies, and empowerment of local groups. In the "Shared Space" of the Millennium Institute (Glenn and Gordon, 1997), resources are shared more equitably for the benefit of all and the safety of humanity. The Shell "Sustainable World" (1996, 1998) and the WBCSD (1998) "Geopolity" and "Jazz" also examine sustainable futures.

Implications of sustainable energy scenarios

The divergence among the three cases described in this chapter reflects different assumptions for a number of driving forces of future development, such as demographic changes and economic growth. Assumptions about future technological change are the most important determinants of how the scenarios unfold. These assumptions include the effectiveness of RD&D and the direction and rate of technological diffusion (including lock-in effects and learning curves). Future capital investments and financing are also crucial determinants of future energy development, as are global energy trade patterns. Finally the impact of environmental changes at local, regional, and global levels will also drive change and energy developments.

RD&D trends and requirements and technological diffusion

The development of clean, efficient, affordable, reliable energy systems is a common characteristic of most sustainable energy scenarios. An important prerequisite for such future technology developments is sufficient investment in RD&D. But this alone is not a guarantee for success. Radically new technologies need to be introduced into the marketplace and (if successful) need to be pervasively diffused to contribute to sustainability. Incremental improvement of existing technologies is likely to fall short of changing technoeconomic paradigms, as is foreseen in the three scenarios characterised by sustainability. In fact, all these scenarios rely on pervasive diffusion, over a long time period, of new technoeconomic systems in the energy system - from a combination of advanced, highly efficient energy extractions, to conversion and end-use technologies, to new, clean energy carriers such as hydrogen.

These technology needs for achieving sustainability are in stark contrast to recent developments. RD&D efforts have increased substantially in most OECD countries. But energy-related RD&D has declined in all of them except Japan and Switzerland. In share of GDP, energy-related efforts may have declined by as much as 10 percent a year on average in OECD countries. It has been argued that this decline in public RD&D funding is more than compensated for by private sources as a consequence of recent energy privatisation and liberalisation. But the tentative evidence indicates

that this is not necessarily true for investments in radical new technologies, and that private-sector energy RD&D focuses more on incrementally improving technologies and may be declining. For example, private energy-related RD&D has fallen by nearly a third in the United States during the past five years, while RD&D in other sectors has increased (chapter 12).

Finally, it has been claimed that the deployment of new energy technologies has occurred at an unprecedented rate in recent years despite the declines in RD&D funding. This is supposed to indicate that there are plenty of funds available for attractive new technologies. Perhaps this is true, but many of the energy technologies that have been deployed successfully in recent years - from combined-cycle gas turbine to horizontal drilling - were developed long ago, when RD&D funding was plentiful. There also have been important spillovers from other sectors; for example, the development of gas turbines benefited from enormous progress on both military and civilian jet engines. But new competitive pressures have probably contributed to price declines and wide diffusion of these technologies.

A strong conclusion for a whole range of sustainable scenarios is that a substantial increase in RD&D for new energy technologies is needed. Otherwise most clean, efficient fossil and renewable technologies may not reach competitiveness with traditional options. Significant improvements

in these technologies are required as traditional technologies improve as well. This is not, however, an appeal to return to the types of exclusively public expenditure programs on energy RD&D of past decades. The paradigm has shifted now towards a balance between publicly and privately funded basic research and towards far more reliance on incentives to promote private RD&D and market applications, for example through tax and regulatory incentives for innovation.

These kinds of advances in knowledge and technology are likely to be as important for achieving a sustainable future as they were for explaining the productivity growth in today's industrialised countries. In the original study by Solow (1956) it was estimated that 87 percent of per capita productivity growth was due to technological change (the remainder was attributed to increases in capital inputs). The contribution of technical progress to pollution abatement is even greater: as the chapters on energy technology (7 and 8) and the economy (11) show, innovations in pollution control can often cut emissions by 95 percent, and potentially completely in some cases. Advances in knowledge thus do not simply contribute to economic development in general but also help achieve a higher degree of affluence, equity, and environmental compatibility.

Technological diffusion occurs over a long period of time, from a new technology's

first introduction to its pervasive adoption.

Economic growth theory suggests that different capital and labour productivities across countries lead to different productivity growth rates and hence to conditional convergence across economies. As Rostow (1990) explained, the "poor get richer and the rich slow down". This relative convergence of the poor and rich stems from the assumption of diminishing returns on capital. Additional convergence potentials may accrue for economies with a higher ratio of human to physical capital. In terms of a functional relationship for future developments, therefore, per capita GDP growth rates are expected (all other things being equal) to be higher for economies with low per capita GDP levels. Notwithstanding many frustrating setbacks like the recent 'lost decade' for economic catch-up in Africa and Latin America, empirical data indicate that the convergence theorem holds. The evidence put forward by Barro (1997) and Barro and Sala-I-Martin (1995), based on the experience of some 100 countries in 1960-85, shows per capita GDP growth rates as a function of GDP per capita levels after accounting for all other salient influencing variables (such as education, inflation, terms of trade, and institutional factors).

Many sustainable scenarios have in common this kind of relative economic convergence and catch-up between today's developing and industrialised

regions in the next 100 years. The successful diffusion of new technologies and different consumption patterns are therefore important prerequisites for achieving sustainability in such scenarios.

With a few notable exceptions (for example, the scenario developed by Lazarus and others, 1993, and the case C scenarios presented in the IIASA-WEC study), the challenge of exploring conditions for closing the income gap between developing and industrialised regions appears to be a fundamental challenge for scenarios that describe sustainable development. Differential economic growth rates can close a part of this gap; the other part needs to be closed through additional measures ranging from accelerated rates of technological diffusion to more equitable income and resource distribution. For example, the C scenarios incorporate a challenging, broad portfolio of environmental control technologies and policies, including incentives to encourage energy producers and consumers to use energy more efficiently and carefully, 'green' taxes (levied on energy and carbon), international environmental and economic agreements, and technology transfer.

Case C reflects substantial resource transfers from industrialised to developing countries, which spur growth and eradicate poverty. Specifically, C assumes that energy and carbon taxes are applied universally, albeit at different rates and timing, and are revenue neutral. The proceeds from these taxes in OECD countries are recycled as resource

transfers to developing countries and are used to promote energy infrastructure, clean technologies, efficiency, and conservation. Such transfers help solve part of the scenarios' development problem, which is fundamental for a sustainable world. Solving the other part of the problem entails revitalising international programs to address world poverty. These poverty alleviation aspects of achieving sustainability are implicit in the scenarios - and include investment in energy and environmental ends, but more important in education, health, security against natural disasters, and so forth.

Capital requirements and financing

Capital investment is crucial for energy development. Both the overall development of and structural changes in energy systems result from investments in plant, equipment, and energy infrastructure. Because adequate and affordable energy supplies are critical for economic growth, any difficulties in attracting capital for energy investment can slow economic development, especially in the least developed countries, where 2 billion people have yet to gain access to commercial energy services. And - although energy investment accounts for only a small share of the global capital market - the availability of the capital needed for a growing energy sector cannot be taken for granted but depends on prices and regulations that permit investors to earn rates of return that are competitive with other opportunities offered by international capital

markets. This is especially the case for sustainable development paths, which require high levels of investment in new technologies and conservation measures that may not be initially competitive with their traditional counterparts.

Capital markets have been growing faster than total GDP for quite some time, and this trend is unlikely to change. Present annual global energy investments are approximately 7 percent of international credit financing of about $3.6 trillion (Hanke, 1995). With capital markets growing relative to GDP, and assuming largely stable future energy investment ratios, capital market size does not appear to be a limiting factor for energy sector finance today and is not likely to be one across a wide range of scenarios.

Very few scenarios in the literature give a detailed account of energy-related investments. Even fewer describe investments that will promote sustainable energy futures. Thus estimates of global capital requirements for energy development are often based on back-of-the-envelope calculations of aggregate energy investment indicators for several major energy-consuming countries that have been extrapolated to the rest of the world. These estimates tend to be highly influenced by present market realities and short-term market expectations and necessarily incorporate a number of ad hoc (and not necessarily consistent) assumptions about the relationship between income growth and energy requirements.

For example, if energy intensities are assumed to increase, capital requirements will, other things being equal, differ significantly from scenarios in which energy intensities decline. Investments are likely to grow faster than GDP in the former case and slower than GDP in the latter. Capital estimates also depend greatly on the assumed costs of different technologies, including infrastructure, and the projected energy mix. As a result, comparisons among estimates of future investment requirements must recognise that each reflects a set of assumptions consistent with a specific energy-economy-environment scenario.

The IIASA-WEC scenarios provide a comprehensive assessment of energy-related investment requirements on the basis of detailed bottom-up cost calculations for the entire energy sector, extending from resource extraction (such as coal mining and oil exploration) through development and production to delivery of energy products to final consumers. The estimates of energy investments do not include, however, those required to achieve more efficient services or structural changes that lead to greater efficiencies. Each technology - an oil platform, gas pipeline, liquefied natural gas (LNG) terminal, electricity generating plant, district heat grid, and so forth - is characterised by a set of technoeconomic parameters, one of which is investment cost in dollars per unit of installed capacity. These costs are then aggregated into the total investment requirements for the entire energy sector. But because these cost estimates were derived during the 1990s (for the base year 1990), they do

not reflect more recent changes, such as declines in energy costs.

A conclusion consistent across all six IIASA-WEC scenarios is that the capital requirements of the energy sector will be extremely large relative to current standards, but will not be infeasible. During the next 30 years capital requirements across the scenarios are estimated to be $12-17 trillion, measured at market exchange rates and 1998 dollars (or $10-15 trillion in 1990 dollars; this is to be compared with 1990 gross world product of about $20 trillion; see table 9.1). (In 2000-20, investment requirements are estimated to be $9-$13 trillion, 1998 dollars.) Figure 9.7 shows this range of cumulative global energy investment requirements between 1990 and 2020. They are desegregated into investments in the electricity sector, other energy conversion systems, and energy supply (extraction, upgrading, transmission, and distribution) for three major world regions; table 9.1 shows the cumulative investments for 2020-50 and 2050-2100. Note that capital requirements are lowest for the case C scenarios that describe sustainable development paths. These scenarios' relative advantage of substantially lower energy financing requirements is an important indicator of the high economic value of energy efficiency and conservation. But the costs of energy end-use changes are not included in the assessment.

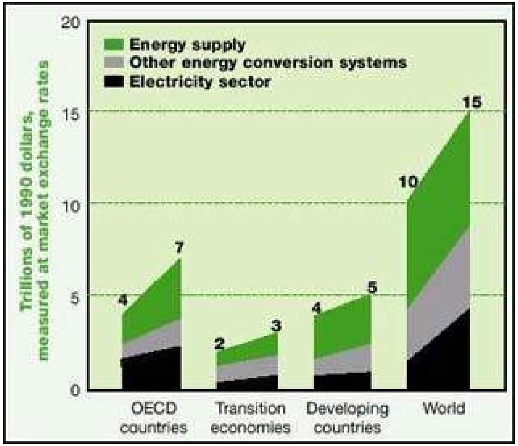


FIGURE 9.7. CUMULATIVE ENERGY INVESTMENTS ACROSS SIX SCENARIOS, 1990-2020

The highest investments refer to case A and the lowest to case C scenarios.

Source: Nakicenovic, Grbler, and McDonald, 1998.

As a share of GDP, global energy investments range from 1.5 to 1.9 percent across the scenarios. This is in line with historical norms: During the early 1990s investment averaged just over 1 percent of global GDP (ranging from $240-280 billion a year). In the scenarios they are highest in the transition economies of Europe and Asia, where they range up to 7-9

percent of GDP. These high investment needs are a legacy of the high energy intensity of the former centrally planned economies and recent declines in investment that went along with economic recession. The result is a substantial need to reconstruct and upgrade energy infrastructure. Another important aspect of future energy investment is that the share of developing regions rises sharply, from today's 25-30 percent to 42-48 percent, and these regions become the largest capital investment market in all scenarios.

Overall, energy investments in the scenarios decrease as a share of GDP throughout the world. But the challenge will be that an increasing fraction of capital requirements will need to be raised from the private sector, where energy needs will face stiffer competition and return-on-investment criteria. Also most investments must be made in developing countries, where both international development capital and private investment capital are often scarce.

Technological diffusion

Technological progress is central to all scenarios that describe sustainable development. The direction of technological change is of crucial importance in these scenarios. To varying degrees they all envisage a transition from reliance on fossil energy sources to clean fossil options, renewable energy sources, and in some cases to safe nuclear energy. But

they require the development and diffusion of radical new technoeconomic systems. The IIASA-WEC scenarios illustrate this by different directions of technological change in the energy system within the framework of the three case A scenarios. Energy systems structures range from continued reliance on fossil-intensive development paths to high rates of decarbonisation. Otherwise the scenarios share the same development of other driving forces such as population, economic growth, and energy demand. Clearly the fossil-intensive scenarios do not meet sustainability criteria - unless they radically reduce emissions, including carbon removal and storage. Other implications of these alternative technological development paths are equally important. This illustrates that the direction of technological change can be as important for achieving sustainable development as all other driving forces combined.

Technological diffusion occurs over a long period of time, from a new technology's first introduction to its pervasive adoption. For energy technologies diffusion time may range from 10-20 years all the way to 100 years. For example, the diffusion of motor vehicles or air conditioning systems usually takes 10-20 years. In contrast, the diffusion of new energy systems consisting of numerous individual technologies, such as a shift to renewable sources, might take almost 100 years. A principal conclusion of many sustainable energy scenarios is that the long-term transition to new energy technologies will largely be determined by technological choices made in the next 10-30 years. There is a need to anticipate technical

characteristics - such as performance, cost, and diffusion - of new energy technologies such as photovoltaics, hydrogen production, and fuel cells; the long-term diffusion, transfer, and performance of these technologies depends on near-term RD&D and investment policies and decisions. If new technologies are not developed through dedicated RD&D efforts, they will not be diffused and will not be available when needed. Diffusion is an endogenous process. This illustrates path dependence in technological diffusion; because there is a virtual lock-in to the development path formed by many individual, related decisions, other possibilities are excluded (for example, see Grbler, 1998b).

These lock-in effects have two implications. First, early investments and early applications are extremely important in determining which technologies - and energy resources - will be most important in the future. This means that there needs to be an early investment in sustainable technologies if the sustainable development path is to be achieved. Second, learning and lock-in make technology transfer more difficult. This means that - in this context - the difference between diffusion and transfer disappears; they are parts of the same process. Successfully building and using computers, cars, and power plants depends as much on learning through hands-on experience as on design drawings and instruction manuals. And a technology that is tremendously productive when supported by complementary networks of suppliers, repair workers, training programs, and so forth, and by an infrastructure that has co-

evolved with the technology, will be much less effective in isolation.

Technology costs and performance - including energy efficiency in particular - improve with experience, and there is a common pattern to such improvements for most technologies. This pattern of increasing returns to diffusion and transfer is important for the transition to sustainable energy futures, and it needs to be incorporated more explicitly into the scenarios.

In case A, there are substantial learning-curve effects for all new, and currently marginal, energy production and conversion technologies. These developments are consistent with the technological perspectives given in chapters 7 and 8. Thus there are considerable advances in hydrocarbon exploration, extraction, and conversion, carbon removal and storage, renewable and nuclear electricity generation, and hydrogen and biofuel production and conversion. For case B, the learning-curve effects are also substantial, especially for new, environmentally desirable technologies. But they lag on average 30 percent behind those in case A, which is consistent with the less concentrated RD&D efforts in case B. For case C, learning-curve effects by design favour low-carbon fossil and renewable technologies. These technologies benefit from improvements equal to those in case A. All other technologies develop as in case B.

International energy trade and security

Generally a lot of trade takes place in the scenarios, ranging from capital goods to energy. Energy-related trade in capital goods includes plant and equipment - required, for example, for the adoption of environmentally friendly technologies. So not only trade in energy is important in the scenarios. An analysis of the energy trade flows implied by the scenarios reveals a general decline in the share of primary energy (equivalent) that is traded world-wide. Currently about 18 percent of global primary energy is traded among the main world regions (as defined in the IIASA-WEC study). This is in close agreement with the true country-by-country figure for 1990 of about 19 percent (Nakicenovic, Grbler, and McDonald, 1998). Crude oil and oil products are currently dominant, accounting for 78 percent of global energy trade; coal accounts for 13 percent and natural gas for 9 percent. By 2050 primary energy traded declines to between 11 and 16 percent. In comparison, oil and gas imports to Western Europe were about 34 percent of primary energy consumption in 1990, and oil imports to North America were about 16 percent of primary energy consumption the same year. But absolute volumes continue to increase in the scenarios - up to a factor of 2.5 for case A and a factor of 1.7 for case B. The increase in case C is much lower, at 10-40 percent. Energy trade in case C is limited primarily to sustainable energy forms (such as biomass, methanol, ethanol, and to a lesser degree hydrogen) and actually shrinks beyond 2050. This indicates that even in case C scenarios world trade in oil and gas continues to increase, despite a shift towards stronger reliance on renewable energy sources throughout the new century.

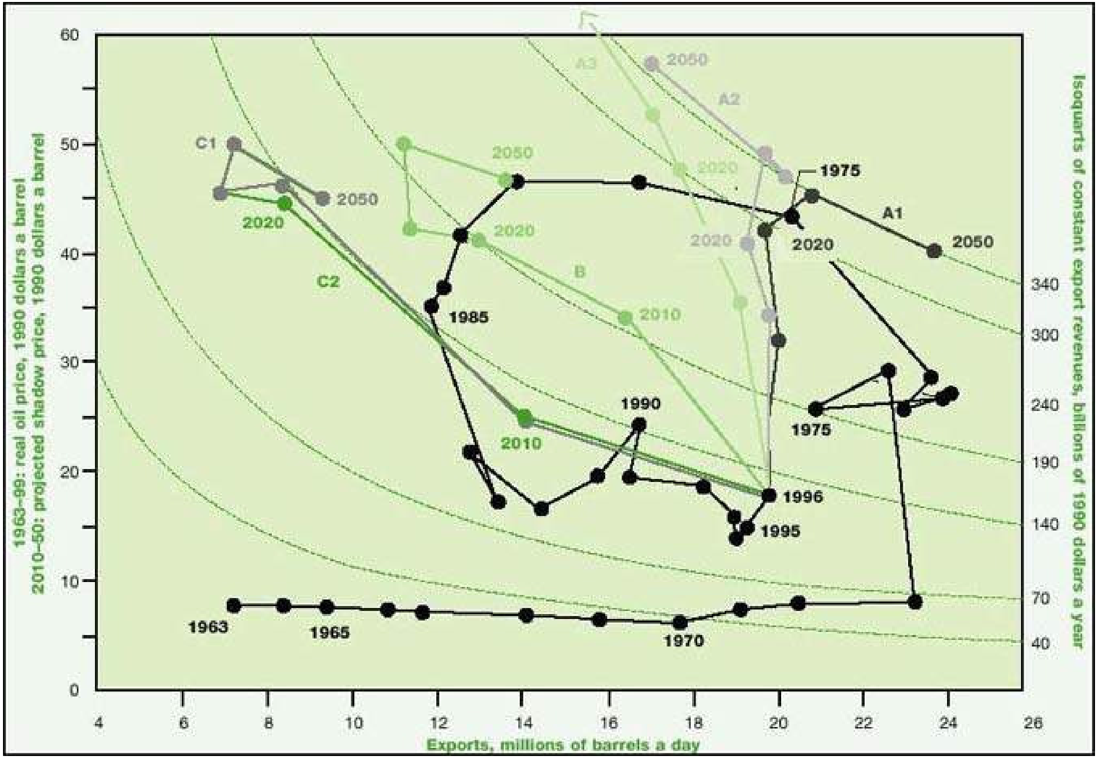


FIGURE 9.8. OIL EXPORT QUANTITIES, PRICES, AND REVENUES FOR THE MIDDLE EAST AND NORTH AFRICA, 1963-96, AND IN SIX SCENARIOS, 2010-2050

Source: Nakicenovic, Grbler, and McDonald, 1998.

The overall geopolitical shift in energy use from industrialised regions to today's developing regions across all scenarios is also reflected in energy trade. In 1990 OECD imports accounted for 84 percent of international energy trade. By 2020 OECD-country shares drop to 55 percent in case C and 65 percent in case B, and by 2050 to 10 percent in case C and 34 percent in case A. This shift is likely to erode the current position of OECD countries as the dominant energy buyers. Conversely import security concerns, which traditionally have been strong in import-dependent Western Europe and Japan, will increasingly be shared by today's developing regions (chapter 4). Concerns about absolute import needs will also grow in developing countries in comparison with OECD countries.

The prospects for oil-exporting regions are bright in the long run across all scenarios, and, at least through 2050, oil revenue is unlikely to be below $170 billion (in 1998 dollars) a year in the Middle East and North Africa. But there are differences among the three cases, as shown in figure 9.8. In case C, environmental policies reduce fossil fuel (that is, taxes and regulation) demand and cause declining exports, but rising export prices keep revenue constant. In cases A and B, technological change and the speed at which reserves are replenished from the resource base (chapter 5) determine export prices, export volumes, and revenues. In case A, greater technological progress than in case B enables higher export at slightly elevated export prices, and long-term revenues may exceed $360 billion (in 1998 dollars) annually. The slower the rate of technological

change, the more important the price component becomes in revenue generation. Export volumes slip as reserves are replenished more slowly, prices rise, and revenues vary as a function of the scenario-specific oil substitution possibilities. Long-term export revenues for the region exceed $360 billion a year in case A and are at least $240 billion a year in case B, and thus are substantially higher than at present.

BOX 9.3. ENERGY SCENARIOS FOR THE NEWLY INDEPENDENT STATES OF THE FORMER SOVIET UNION

Two scenarios of future energy developments for the former Soviet Union, considered to include characteristics of sustainable development from the regional perspective, are labelled “optimistic” and “probable” (Makarov, 1999). The optimistic scenario is similar in character to IIASA-WEC case A in that rapid globalisation of markets, vigorous technological development, and increasing concerns for the environment are assumed. The probable scenario has a number of characteristics in common with IIASA-WEC case B. It basically represents a world where the optimistic scenario is implemented more moderately.

After the recovery from the current recession in 2000-10, both scenarios envisage rapid economic growth. In the optimistic case, per capita income levels reach $10,000 by about 2030; in the probable scenario, by about 2040. Energy intensities are also assumed to improve, with economic growth reversing the recent increases as the consequence of the deep recession.

The primary energy requirements range from 44 exajoules in the probable scenario to 50 exajoules in the optimistic scenario by 2050, in comparison with 57 exajoules in 1990. Energy intensity improvements lead to generally lower energy requirements despite vigorous economic development. These energy requirements correspond to 137-145 gigajoules per capita by 2050, in comparison with almost 200 gigajoules per capita in 2050.

Already in 1990, 50 percent of final energy was delivered to consumers in the form of high-quality energy carriers such as electricity, gas, and district heat. The quality of final energy improves further in both scenarios.

Electricity and gas exports grow consistently in both scenarios, providing clean fuels to emerging energy markets in Europe and Asia. Gas is an essential transition fuel in the scenarios because it is so well-matched to the pervasive trend in consumer preferences for high-quality, clean, flexible convenient final energy delivered by grids.

Both scenarios are characterised by declining energy sector investments as a share of GDP, to 2.3-3.0 percent by 2050. In absolute terms the cumulative financing requirements between 2000 and 2020 are in the range of $500-$700 billion.

Concerns about possible climate change are considered limited in the two scenarios for two reasons. First, the recession of the 1990s left the region with other pressing economic, social, and environmental priorities. Second, the energy development outlined in the two scenarios results in emissions that are well below the 1990 levels specified for Russia and Ukraine in the Kyoto Protocol. The difference between these specified emissions levels and the much lower emissions in the two scenarios through 2050 (way beyond Kyoto commitments) is an asset potentially worth money if and when the Kyoto Protocol enters into force.

Another potential exporter of fossil energy is the former Soviet Union, where natural gas will be the principal energy export (box 9.3). Gas exports from this region increase for all scenarios, from 4 exajoules in 1990 to a relatively narrow range of 11-12 exajoules in 2020 and diverge afterwards across the scenarios, as shown in figure 9.9. By 2050 annual exports range up to 27 exajoules, and annual revenues reach $150 billion (1990 dollars; $180 billion in 1998 dollars).

Overall, crude oil and oil products remain the most traded energy commodities through 2050. The spread is quite large, ranging between 77 percent in case A and 33 percent in case C. After 2050 methanol, piped natural gas, LNG, and to a lesser extent also hydrogen become the key traded energy commodities. Electricity, an important component of regional energy trade, and is thus considered in the scenarios but is not important in global energy trade. As noted above, trade and investment in technologies will be very important.

In general the global energy trade pattern shifts from primary to secondary energy forms, which improves trade flexibility and lowers energy security concerns. For example, methanol and hydrogen can be produced from a number of primary sources ranging from coal to biomass (chapters 7 and 8). Biofuels and eventually hydrogen production leave more value added in the exporting regions than the export of primary energy. Exporting secondary energy forms becomes a staple source of income for a number of developing regions. Nevertheless oil- and gas-exporting regions generally increase their export revenues even in the more sustainable scenarios, indicating that improved energy efficiency and a shift towards other energy sources would not necessarily erode the position of energy-exporting regions.

Environmental issues at the local and regional scales

Local environmental impacts are likely to continue to take precedence over global change in the achievement of sustainable energy developments. According to the IIASA-WEC study, the natural capacity of the environment to absorb higher levels of pollution is also likely to become a limiting factor on the unconstrained use of fossil fuels. This also appears to be the case in many other sustainable energy scenarios. Increasing income would also lead to a higher demand for cleaner energy end uses in rural areas world-wide. This includes a shift away from cooking with wood and coal in inefficient traditional open fireplaces. Such a change would reduce

indoor pollution levels, currently estimated to be 20 times higher than in industrialised countries.

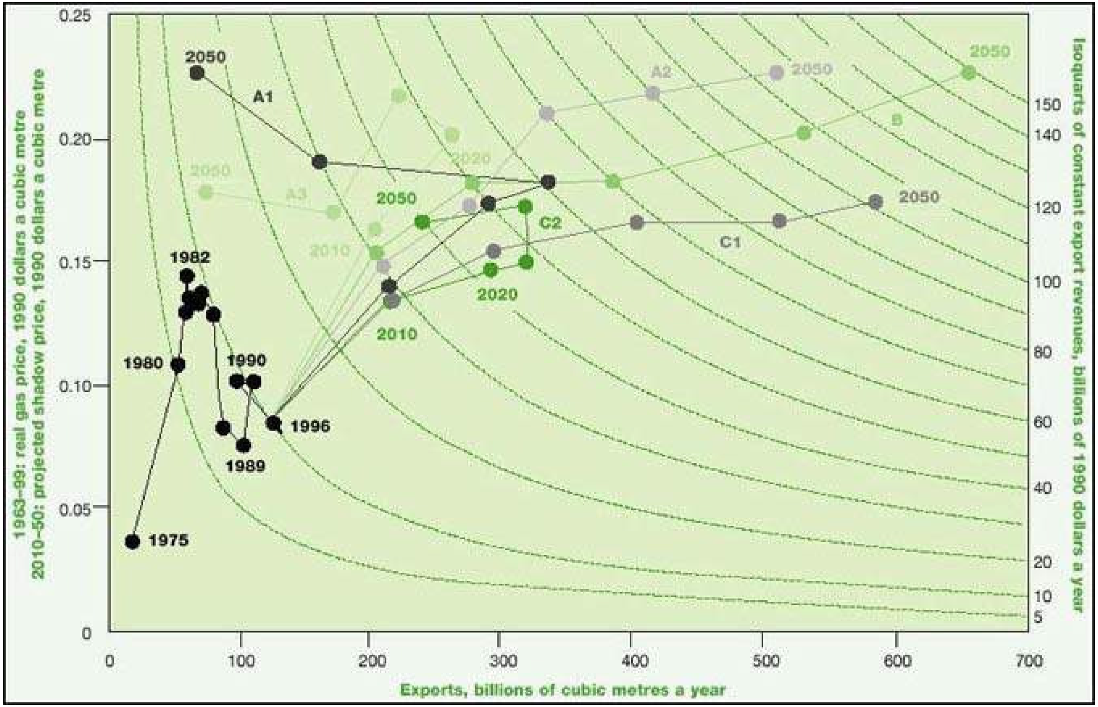


FIGURE 9.9. NATURAL GAS EXPORT QUANTITIES, PRICES, AND REVENUES FOR THE FORMER SOVIET UNION, 1975-96, AND IN SIX SCENARIOS, 2010-2050

Source: Nakicenovic, Grbler, and McDonald, 1998.

A particularly urgent environmental problem in densely populated metropolitan areas is the high concentration of particulate matter and sulphur dioxide. Here cleaner fuels, such as natural gas, and active abatement measures will be required. Regional air pollution could also prove problematic, especially in the rapidly growing, densely populated, coal-intensive economies of Asia. In the booming cities of China and Southeast Asia, high levels of air pollution must be addressed with appropriate measures (box 9.4).

According to the findings of the IIASA-WEC study, one of the scenarios (A2), with a high dependence on coal (assuming no abatement measures), would result in high sulphur dioxide emissions and significant regional acidification, causing key agricultural crops in the region to suffer acid deposition 10 times the sustainable level before 2020. Figure 9.10 shows excess sulphur deposition above critical loads in Asia for the unabated A2 scenario. According to this scenario, emissions could triple in Asia by 2020, and ambient air quality in South and East Asia could deteriorate significantly in both metropolitan and rural areas. Sulphur deposition would reach twice the worst levels ever observed in the most polluted areas of Central and Eastern Europe (for example, in the so-called black triangle between the Czech Republic, Germany, and Poland). Of critical importance for economically important food crops in Asia is that unabated

sulphur emissions would cause critical loads to be exceeded by factors of up to 10. As a result severe losses in crop production could occur over large areas of Asia. In contrast to this dire outlook of possible consequences of unabated sulphur emissions in coal-intensive A2, A3 and C are relatively benign, leading to some, but not alarming, excess emissions in the future; perhaps more important, by the middle of the 21st century global sulphur emissions would be reduced to well below current levels.

BOX 9.4. ENERGY SCENARIOS FOR CHINA

Five scenarios are considered for China. The first is a baseline scenario; the other four illustrate different strategies to achieve more sustainable development from a regional perspective (Zhou, 1999).

The baseline scenario is intended to represent a practical, feasible fulfilment of future energy demand with low risk. It is assumed that GDP will expand by 22.7 times between 1990 and 2050, while energy demand will increase relatively modestly by about 1.7 times during the same period. This is due to vigorous improvement of energy intensities in combination with rapid economic growth. The future energy supply in the baseline scenario continues to be dominated by coal, however, with substantial technology and efficiency improvements. The main limitations and concerns are related to potential adverse environmental impacts. In particular, this coal-intensive baseline scenario is likely to lead to air pollution and energy-related emissions that substantially exceed acceptable levels. This is the main reason for the formulation of alternative development paths that fulfil the development objectives of China, but with substantially lower adverse environmental impacts.

The four sustainable scenarios explore alternative measures and policies to reduce the environmental burden of energy. The first scenario focuses on strengthening energy conservation. It is estimated that the energy conservation potential, if fully utilised, could reduce energy demand in China by 12 percent relative to the baseline by 2050. The second alternative scenario focuses on adoption of clean coal technologies. The main advantage of this scenario is that it would allow for the use of large domestic coal resources while curbing air pollution and sulphur emissions. But it would still lead to high carbon dioxide emissions. The third scenario focuses on renewable energy sources as replacements for coal. The fourth scenario focuses on nuclear energy, including breeder reactors, as a replacement for coal.

Combinations of these alternative scenarios were also considered, resulting in a substantial decrease in the ultimate share of coal to below 40 percent by 2050. Nevertheless coal remains the most important energy source across all these alternatives. Thus one of the conclusions is that a high priority should be placed on developing and diffusing clean coal technologies - in addition to conservation - in the four more sustainable scenarios. This strategy could lead to mitigation of 40 percent of future sulphur emissions (for example, in the second alternative scenario, at relatively modest increases in investment requirements, sulphur emissions decline from 23.7 million tonnes in 1995 to 13.5 millions tonnes in 2050). The energy conservation scenario had the advantage of low financing requirements and the lowest carbon dioxide emissions - but at the expense of a 60 percent increase in sulphur emissions. In contrast the clean coal scenario achieves a 40 percent reduction of sulphur emissions but has the highest carbon dioxide emissions. The renewable and nuclear energy scenarios lead to reductions in emissions at all scales, but the reductions in sulphur and carbon dioxide are not very large (10 percent and 20 percent), while the investment costs are very high.

People world-wide already suffer from local and regional air pollution, and both governments and individuals are taking steps to improve the situation. These actions are part of the drive towards higher efficiencies and cleaner fuels and may also contribute to the shift towards a more sustainable development path. They also have the positive spin-off effect of reducing carbon emissions and possible global warming, although that is not their principal motivation.

Consequently emissions of sulphur aerosol precursors portray very dynamic patterns in time and space in most sustainable energy scenarios, in contrast to the development in many reference scenarios (see figure 9.10). A detailed review of long-term global and regional sulphur emission scenarios is given in Grbler (1998a). Most recent scenarios recognise the significant adverse impacts of sulphur emissions on human health, food

production, and ecosystems. As a result scenarios published since 1995 generally assume various degrees of sulphur controls to be implemented in the future and are thus substantially lower than previous projections. Other developments, such more sulphur-poor coals and clean fossil technologies and a shift towards renewables and natural gas in scenarios A3 and C, help promote substantial additional emissions reductions as ancillary benefits.

A related reason for lower sulphur emission projections is the recent tightening of sulphur-control policies in OECD countries that continue to dominate global emissions, such as the amendments to the U.S. Clean Air Act and implementation of the Second European Sulphur Protocol. These legislative changes were not yet reflected in previous long-term emission scenarios, as noted in Alcamo and others (1995) and Houghton and others (1995). The median from newer sulphur-control scenarios is consequently significantly lower relative to the older scenarios, indicating a continual decline in global sulphur emissions.

Scenarios A3 and C include a host of environmental control measures that help reduce emissions of sulphur dioxide and other pollutants. This is consistent with most of the scenarios that lead to a long-term, sustainable decline of particulate and sulphur levels, which would return emission levels to those of 1900. As a general pattern, global sulphur emissions do rise initially in recent scenarios, but eventually decline even in absolute

terms after 2050. The spatial distribution of emissions changes markedly, generally from OECD regions to rapidly developing regions in Asia, and varies across scenarios.

In the sustainable IIASA-WEC scenarios (A3 and C), emissions in OECD countries continue their recent declining trend, reflecting a tightening of control measures. Emissions outside OECD countries, most notably in Asia, initially rise and then decline, resembling the current trend in OECD emissions. The reductions are especially pronounced in the C scenarios because of a virtual transition to the post-fossil era by 2100, essentially eliminating sulphur emissions. A3 leads to substantial sulphur declines, even though it has the same economic growth prospects as A2. There are many reasons. First, clean coal technologies, such as gasification, remove sulphur as an inherent property of the conversion process. Then there is a shift in fossil energy supply to low sulphur-grade coals, higher shares of natural gas, and later to non-fossils as well. Over the long term sulphur emissions decline in both scenarios throughout the world, but the timing and magnitude vary.

Climate change: Land use and other global issues

One important implication of the varying pattern of particulate and sulphur emissions across the scenarios is that the historically important, but uncertain, negative radiative forcing of sulfate aerosols may decline in the

very long run (Hulme, 1997; chapter 3). This means that the current cooling effect on the climate that results from the emissions of particulates and sulphur aerosols would diminish, causing additional, spatially different patterns of climate change. This view is also confirmed by the model calculations reported in Subak, Hulme, and Bohn (1997), Nakicenovic, Grbler, and McDonald (1998), Nakicenovic (2000), Smith and others (forthcoming), and Wigley (1999) and is based on recent long-term greenhouse gas and sulphur emission scenarios. This means that precursors of air pollution and acidification at the local and regional levels have an important role in global climate change. But emissions of greenhouse gases such as carbon dioxide continue to be the main source of climate warming.

Cumulative future CO_2 emissions are in the first approximation indicative of potential climate change (chapter 3). Carbon dioxide emissions are the major anthropogenic source of climate change, and energy is the most important source of CO_2 emissions. A number of energy scenarios in the literature account for the emissions of other greenhouse gases and thus provide a more complete picture of possible implications for climate change. For simplicity, only energy-related sources of CO_2 emissions are evaluated here.

Figure 9.11 shows the CO_2 emissions of the six IIASA-WEC scenarios

superimposed on the emissions range of the energy scenarios from the literature. The range is very wide by 2100, from more than seven times current emissions to almost none for scenarios that assume a complete transition away from fossil energy. The emission profiles are different across the range of scenarios. Most portray a continuous increase throughout the 21st century, whereas the sustainable scenarios generally have lower, more dynamic emission profiles. Some of them curve through a maximum and decline.

For the scenarios in the literature, the distribution of emissions by 2100 is very asymmetrical and portrays a structure resembling a trimodal frequency distribution: those with emissions of more than 30 gigatonnes of carbon (20 scenarios), those with emissions of 12-30 gigatonnes of carbon (88 scenarios), and those with emissions of less than 12 gigatonnes of carbon (82 scenarios). Most of the scenarios in this lowest cluster are situated at 2-9 gigatonnes of carbon; this cluster appears to include many of the sustainable energy scenarios, and the second and third clusters most likely include only a few of them. The lowest cluster may have been influenced by many analyses of stabilising atmospheric concentrations, for example at 450 and 550 parts per million by volume (ppmv), in accordance with the United Nations Framework Convention on Climate Change (UNFCCC, 1992).

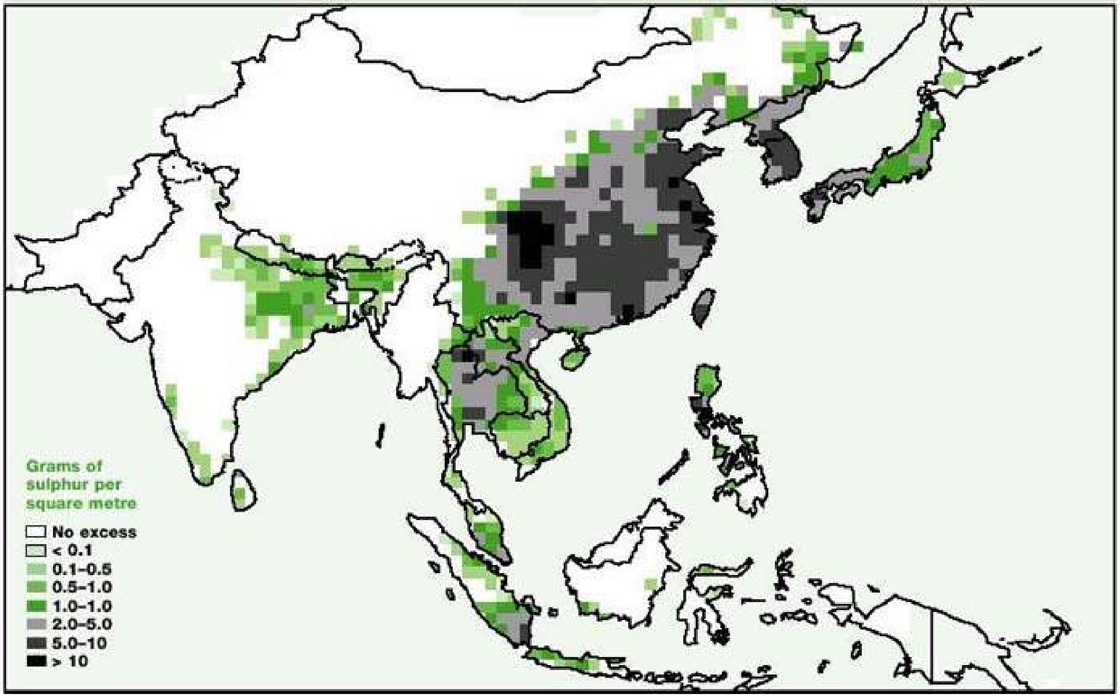


FIGURE 9.10. EXCESS SULPHUR DEPOSITION ABOVE CRITICAL LOADS IN ASIA FOR AN UNABATED A2 SCENARIO, 2020

Source: Amann and others, 1995.

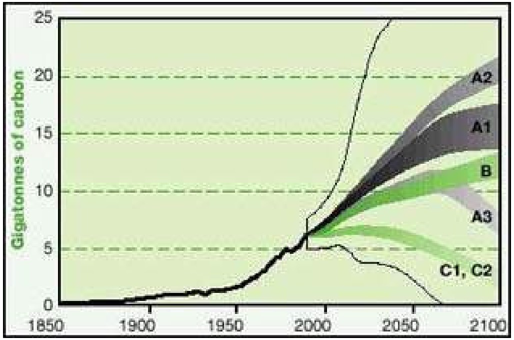


FIGURE 9.11. GLOBAL CARBON EMISSIONS FROM FOSSIL FUEL USE, 1850-1990, AND IN SIX SCENARIOS, 1990-2100

For each scenario, the range shows the difference between gross and net emissions. Gross emissions are actual carbon dioxide released into the atmosphere. Net emissions include deductions for carbon absorption (through biomass regrowth and sequestration). The figure also shows the wider range of emissions for 190 scenarios in the literature. The vertical line that spans the scenario range in 1990 indicates the uncertainty across the literature of base-year carbon emissions.

Source: Nakicenovic, Grbler, and McDonald, 1998; Morita and Lee, 1998.

The cumulative carbon emissions between 1990 and 2100 are 540

gigatonnes in the case C scenarios, 1,000 gigatonnes in B, 1,210 gigatonnes in A1, 1,450 gigatonnes in A2, and 910 gigatonnes in A3. Thus A3 and C have both the lowest cumulative emissions and lowest annual emissions towards the end of the century. Accumulated emissions across the scenarios between 1990 and 2100 are shown in table 9.1 as well as the resulting atmospheric carbon dioxide concentrations. Table 9.1 shows that the rising carbon dioxide emissions in cases A and B lead to atmospheric carbon concentrations of 530-730 ppmv in 2100. This compares with concentrations of 280 ppmv around 1800 (the beginning of the fossil-fuel age) and current concentrations of 370 ppmv. A3, which includes characteristics of sustainability, leads to the lowest atmospheric concentrations of all A scenarios, about 530 ppmv by 2100. In B and A1, carbon concentrations approach 590 and 620 ppmv, respectively, by 2100. The concentrations of the coal-intensive A2 scenarios are the highest, 730 ppmv by 2100, about twice current levels. Only C scenarios lead to relatively benign concentration levels of less than 450 ppmv (chapter 3).

Thus all scenarios except case C approach the doubling of pre-industrial carbon concentrations. And again in all scenarios except C, concentrations continue to rise throughout the 21st century. On the basis of current knowledge, an increase of carbon concentrations to 600 ppmv by the end of the 21st century could lead to an increase in the mean global surface temperature of about 2.5 degrees Celsius, assuming the mean climate sensitivity and with an uncertainty range of 1.5-4.5 degrees Celsius

(chapter 3).

The C scenarios are the only ones in which carbon concentrations stabilise by 2100, reflecting their ambitious emission reduction profile, from 6 gigatonnes in 1990 to 2 gigatonnes in 2100. After peaking at about 450 ppmv around 2080, carbon concentrations slowly begin to decline as natural sinks absorb excess carbon dioxide. The present carbon cycle models indicate that the emissions reduction to about 2 gigatonnes of carbon a year (or about a third to at most half the current global emissions) is an essential prerequisite for eventually achieving stabilisation of atmospheric concentrations. This is the reason why all other scenarios, including A3, result in continuously increasing concentrations over the time horizon (although A3 is consistent, with stabilisation at 550 ppmv in the 22nd century, assuming that the emissions would further be reduced to about 2 gigatonnes of carbon a year).

Even with its ambitious emission reduction measures, C's atmospheric carbon concentrations rise by up to 90 ppmv during the 21st century. This increase is about equal to the concentration rise since the onset of industrialisation until today (from 280 to 370 ppmv during the past 200 years). Thus even in C, some climate change appears inevitable: perhaps 1.5 degrees Celsius (with an uncertainty range of 1.0-2.5 degrees Celsius) in increased global mean surface temperature. This illustrates both the legacy of our past dependence on fossil fuels and the considerable lead

times required for an orderly transition towards a zero-carbon economy and sustainable development paths. It also illustrates the long residence time of carbon in the atmosphere. Some of the carbon dioxide emissions from Watt's first steam engine are still airborne.

Both IIASA-WEC scenarios with characteristics of sustainability, C and A3, are situated within the lowest cluster with emissions found in the literature, at 2-9 gigatonnes of carbon by 2100. Thus they appear to cover the range of future emissions associated with sustainable development quite well - their range excludes only the most extreme emission scenarios found in the literature. This leads to a substantial overlap in emission ranges across different scenarios. In other words a similar quantification of the driving forces that are all consistent with various concepts of sustainable development can lead to a wide range of future emissions. Because this result is of fundamental importance for assessing climate change and sustainable development, it warrants further discussion.

Another interpretation is that a given combination of driving forces is not sufficient to determine future emission paths. A particular combination of forces, such as those specified in the three IIASA-WEC case A scenarios, is associated with a whole range of possible emission paths. These three A scenarios jointly cover the largest part of the scenario distribution shown in figure 9.11. But only one of them, A3, can be characterised as sustainable. The three scenarios explore different specific structures of

future energy systems, from carbon-intensive development paths to high rates of decarbonisation. All three otherwise share the same assumptions about the driving forces. This indicates that different structures of the energy system can lead to basically the same variation in future emissions as can be generated by different combinations of the other main driving forces - population, economic activities, and energy consumption levels - with basically the same structure of the energy system. The implication is that decarbonisation of energy systems - the shift from carbon-intensive to less carbon-intensive and carbon-free sources of energy - is of similar importance as other driving forces in determining future emission paths.

Figure 9.12 shows the degree of decarbonisation achieved in the scenarios relative to historical trends and the range observed in scenarios from the literature. Carbon intensity of primary energy is shown as an indicator of decarbonisation. The carbon intensity improves across all IIASA-WEC scenarios, but is especially pronounced in the three with characteristics of sustainability, C1, C2, and A3. Sustained decarbonisation requires the development and successful diffusion of new technologies. An important implication of the varying interplay of the main scenario driving forces is that investments in new technologies during the coming decades might have the same magnitude of influence on future emissions as population growth, economic development, and levels of energy consumption taken together. Thus high or low emissions can be associated with a range of social and economic scenarios; the distinguishing feature of the low

emissions and low pollution scenarios is that the policies and technologies are in place to reduce emissions. But countries will be better placed to implement climate-friendly policies if development, in its broadest sense, is successful.

The long-term transition to new energy technologies will largely be determined by technological choices made in the next 10-30 years.

Furthermore decarbonisation also means that other environmental impacts tend to be lower (Nakicenovic, 1996). Thus the energy systems structure of IIASA-WEC scenario A3 is one of the main determinants of its sustainability. In contrast, C scenarios require fundamental changes that encompass energy end use as well. In many ways the transitions in the structures of the energy systems described by the scenarios cannot be seen in isolation from the overall development path towards sustainability. Other scenarios presented in the IIASA-WEC study do not appear to be consistent with the characteristics of sustainability given in table 9.2. This result suggests that the future direction of technological change in the energy system is not only important for reducing the dangers of climate change but can also help nudge the overall development path in the direction of sustainability.

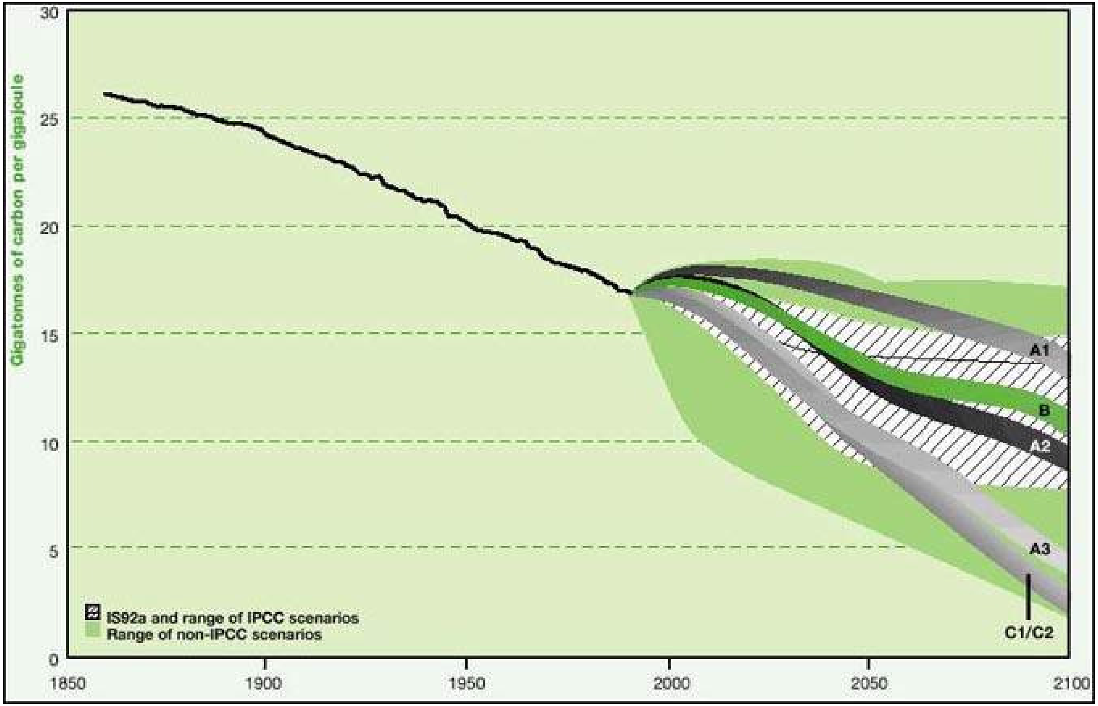


FIGURE 9.12. GLOBAL CARBON INTENSITY OF PRIMARY ENERGY, 1850-1990, AND IN SIX SCENARIOS, 1990-2100, RELATIVE TO THE SCENARIOS FROM THE LITERATURE AND THE IPCC IS92 SCENARIOS

Source: Nakicenovic, Grbler, and McDonald, 1998.

Conclusion

Scenarios are frequently used to assess sustainable development paths. Sustainable futures often are easier to illustrate when they are compared with other scenarios that contradict some of the conditions for achieving sustainability. This is one of the reasons that, in recent studies, sustainable scenarios are usually included among alternative futures. This class of sustainable scenarios can be characterised by low environmental impacts at all scales and more equitable allocation of resources and wealth relative to the current situations and other alternative future energy developments. Recently IIASA and WEC presented a set of six global and regional scenarios (Nakicenovic, Grbler, and McDonald, 1998). Three of the scenarios describe futures with characteristics of sustainability. They are used in this chapter to illustrate the measures and policies for the near-term future that would be required to move away from other alternative but unsustainable development paths. A single reference scenario is used to outline quite positive future developments, but they do not fulfil the essential conditions for achieving sustainability.

One of the three sustainable scenarios, C1, is consistent with most of the conditions and concepts of sustainable development advanced in this report. It presents a rich and green future and presents a fundamentally different future development path that includes both substantial technological progress and unprecedented international cooperation centred on environmental protection and international equity - it includes a high degree of environmental protection at all scales, from eradication of

indoor air pollution to low impacts on climate change, with an active redistribution of wealth and very high levels of energy efficiency and conservation. Thus it fulfils most of the criteria for sustainable development - such as increasing both economic and ecological equity among world regions and countries - and leads to a significantly lower impact on the climate than scenarios with higher greenhouse gas emissions This scenario requires a virtually complete transition away from reliance on fossil energy sources and towards renewable energy sources.

Two variants of this scenario were considered. One of them, C2, foresees a nuclear phaseout by 2100. Both are characterised by a high degree of energy conservation and vigorous efficiency improvements throughout the whole energy system and among end users. Consequently total energy requirements are relatively low relative to the high levels of affluence and quality of life, especially in today's developing regions. The achievement of such a future is indeed challenging, and ranges from devising new RD&D policies to bringing to market new energy technologies, to imposing energy and carbon taxes as incentives for improving energy efficiency and conservation and increasing the shift away from fossil fuels.

Local environmental impacts are likely to continue to take precedence over global change in the achievement of sustainable

energy developments.

The second scenario that includes characteristics of sustainability, A3, is fundamentally different in nature and quite similar to the reference scenario except in the future structure of the energy system. Thus environmental protection and higher levels of affluence are achieved less through changes in levels of energy end use and structure and more through a dedicated decarbonisation of the energy system. Again efficiency improvements are important, and clean fossils such as natural gas are foreseen as gaining much larger shares of global energy needs, along with renewable sources of energy - all contributing towards decarbonisation. Decarbonisation is in part also achieved through more sophisticated energy conversion and processing that includes carbon removal along with more conventional pollutants.

These scenarios illustrate different levels of compatibility between future energy systems and sustainable development. C1 shows the highest level of compatibility with sustainable development characteristics. It exemplifies that the energy aspects of the major issues analysed in chapters 1-4 can be addressed simultaneously. But C1 should be taken only as one illustration of an energy system compatible with a sustainable development future. Other combinations of primary energy sources and energy use levels might be equally or more compatible with sustainable development, as illustrated by C2 and A3, depending on the level of

success with the development and dissemination of new technologies (chapters 6-8). For example, if the carbon sequestration options discussed in chapter 8 are realised, there need not be a large conflict between using coal and reducing carbon emissions, and the fossil fuel share in a sustainable future could be much larger than in C1, as illustrated in A3 scenario.

All sustainable scenarios, including the three IIASA-WEC scenarios described in this chapter in detail, have positive (desirable) and normative (prescriptive) elements. They usually include strong assumptions about desirable futures and prescribe how such futures can be achieved. Common to most is that they show that sustainable futures are not achievable with current policies and prevailing development trends. Their achievement often requires a fundamental change or major paradigm shift. Thus sustainable energy scenarios are often designed to offer policy guidance on managing, for example, an orderly transition from today's energy system, which relies largely on fossil fuels, towards a more sustainable system with more equitable access to resources.

More global studies are considering futures with radical policy and behavioural changes to achieve a transition to a sustainable development path during the 21st century. The great merit of RD&D policies, diffusion, and the adoption of new technologies associated with market-based instruments for environmental change is that radical developments often

proceed gradually from seemingly moderate policies, leading to major improvements over time. But they require continuity over decades so that the cumulative effects of moderate polices can result in radical change. These are some of the crucial characteristics of the three IIASA-WEC scenarios that lead towards sustainable development.

Another central feature of these three scenarios is that adequate provision of energy services and more equitable allocation of resources are crucial for achieving sustainability. At the same time, energy use is a main cause of environmental degradation at all scales and so can inhibit the achievement of sustainability. Thus environmental protection - from indoor pollution to climate change - is an essential element of sustainable development in these scenarios. Rapid development and clean, efficient energy are complementary elements of most of the scenarios. The resolution of these future challenges offers a window of opportunity between now and 2020. Because of the long lifetimes of power plants, refineries, and other energy investments, there is not a sufficient turnover of such facilities to reveal large differences among the alternative scenarios presented here before 2020, but the seeds of the post-2020 world will have been sown by then.

The choice of the world’s future energy systems may be wide open now. It will be a lot narrower by 2020, and certain development opportunities that are forgone now might not be achievable later. There may well be

environmental irreversibilities, but technical changes may still take place, and it is a question of whether they will be too late rather than whether they will occur at all. Perhaps more important is the question of development initiatives directed at eradicating poverty, disease, and illiteracy in the world, and whether they will be timely and sufficient to offset currently inadequate efforts. The achievement of sustainable development dictates a global perspective, a very long time horizon, and immediate policy measures that take into account the long lead times needed to change the system.

Notes

1. Table 9.2 provides a number of indicators that can be used to characterise the achievement of sustainable development in energy scenarios and shows how the three scenarios selected for this assessment fare relative to one another.

2. Energy prices are an important determinant in the short to medium term. But in the long term, technology and policy are more important determinants, although important feedback mechanisms do exist - for example, in the form of induced technical change. As a result future levels of energy demand can vary widely, even for otherwise similar scenario characteristics, in terms of population and level of economic development.

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Chapter 10. Rural Energy in Developing Countries

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ABSTRACT

Supplying modern energy services to the 2 billion people who still cook with traditional solid fuels and lack access to electricity is probably one of the most pressing problems facing humanity today. The amount of energy needed to satisfy the basic needs of rural populations around the world is relatively small, and appropriate technologies are available. However, widening access to modern energy services is limited by the extreme poverty found particularly in the least developed countries.

Living standards in rural areas can be significantly improved by promoting

a shift from direct combustion of biomass fuels (dung, crop residues, and fuelwood) or coal in inefficient and polluting stoves to clean, efficient liquid or gaseous fuels and electricity. Although consumers tend to shift to these modern, higher-quality energy carriers as their incomes rise and the carriers become more affordable, the process is slow. Yet a shift to such carriers can reduce the damage to human health and the drudgery associated with continued reliance on inefficient, polluting solid fuels.

This chapter describes experience with and prospects for improving the technologies used to cook with biomass in several countries, as well as the development of clean, non-toxic cooking fuels. Progress in rural electrification-using both centralised, grid-based approaches and small-scale, decentralised technologies-is also described.

Technological developments alone, however, will not improve access or promote greater equity. New institutional measures are also needed, including financing to cover the initial capital costs of devices and equipment. Energy initiatives will be most successful when integrated with other policies that promote development. And because local populations will ultimately use, maintain, and pay for energy services, they should be involved in making decisions about energy systems.

The lack of adequate energy services in rural areas of developing countries has social dimensions (chapter 2) as well as serious environmental and

health effects (chapter 3). Many of these problems are exacerbated by the almost exclusive reliance of rural populations in most areas on traditional fuels coupled with simple technologies characterised by low energy efficiency and harmful emissions. This chapter thus focuses on technological opportunities, as well as other strategies, for delivering adequate, affordable, cleaner energy supplies to rural areas.

The second half of the 20th century witnessed a strong urbanisation trend and the emergence of megacities (those containing more than 10 million people) in most developing countries. Between 1970 and 1990 the share of people living in cities grew from 28 to 50 percent. But while the rural population relatively decreased during this period, the absolute number of people living in rural areas increased to 3 billion. Despite this, rural development often remains low on government agendas because of increasing demands of growing, politically and economically dominant urban populations. Thus the explosive growth of cities makes it difficult for policy-makers to give rural development the attention it deserves.

The dispersed character of rural populations and their low commercial energy consumption result in poor capacity utilisation efficiency for transmission and distribution systems and other energy infrastructure. Extending an electric grid to a few households in a rural setting can result in energy costs of up to $0.70 per kilowatt-hour, seven times the cost of providing electricity in an urban area (World Bank, 1996). Thus

conventional approaches to extending energy infrastructure are economically inefficient, for both public and private providers-which is another reason the energy problems of rural populations are given low priority by governments.

Because the poor people in rural areas lack access to electricity and modern fuels, they rely primarily on human and animal power for mechanical tasks, such as agricultural activities and transport, and on the direct combustion of biomass (wood, crop residues, dung) for activities that require heat or lighting. Human energy is expended for household work (gathering and preparing biomass for fuel, fetching water, washing clothes), agriculture, and small industry. Biomass fuels are typically used for cooking (which dominates inanimate energy consumption in most warm regions), space heating, heating water for bathing, and meeting some industrial heating needs. Kerosene is used predominantly for lighting, and to a small extent in rural industry. Although much of the world's rural population has no access to electricity generation, many have small battery-operated devices such as radios and flashlights.

Rungs on the energy ladder

Large amounts of human energy are spent gathering fuelwood in many parts of the world, and the burden tends to fall more heavily on women and children.[1] Although there are exceptions, history has generally shown

that when alternatives are available and affordable, consumers opt for more modern energy carriers. As incomes rise and opportunities for using better technologies become available, consumer preferences shift to more efficient, convenient, cleaner energy systems as they become more affordable. That is, consumers move up the energy ladder (chapter 3). This involves a shift to modern energy carriers or to more convenient and energy-efficient conversion devices.

Accelerating the introduction of modern energy is a key strategy for promoting sustainable development in rural areas.

For cooking and other heating purposes, the lowest rungs on the energy ladder involve use of dung or crop residues, with fuelwood, charcoal, kerosene, and liquefied petroleum gas (LPG) or natural gas representing successively higher rungs. For lighting, the lowest rung is represented by fire, followed in turn by liquid-fuelled (such as kerosene) lamps, gas lanterns, and electric bulbs. To do mechanical work, consumers shift from human and animal energy to diesel fuel and electricity as soon as they become available, because they are almost always more cost-effective. Often a synergy between modern energy carriers and more efficient end-use devices occurs.

One of the aims of this chapter is to explore the technological, economic, social, and institutional prospects for more rapidly introducing modern energy carriers into rural areas-which would allow households to move quickly to the top of the energy ladder, ideally skipping (leapfrogging) some of its rungs. Accelerating the introduction of modern energy, then, is a key strategy for promoting sustainable development in rural areas of developing countries. Principally, it involves providing:

- **Clean liquid or gaseous fuels for cooking, and electricity for lighting and other basic household amenities.**
- **Liquid fuels and electricity to mechanise agriculture.**
- **Electricity sufficiently low in cost to attract industrial activity to rural areas (thereby providing well-paying jobs and helping to stem migration to urban settlements).**

It is desirable to skip rungs and advance to the highest rungs on the energy ladder wherever feasible.[2] But because the 2 billion rural poor live in many different circumstances, a complete range of approaches need to be explored, and those that work best in each set of circumstances need to be encouraged. Appropriate public policies should be implemented to accelerate the process and reduce human suffering.

Satisfying basic human needs with modern energy carriers requires relatively small amounts of energy in absolute terms. In regions that do not require space heating, final household energy requirements for satisfying basic needs are estimated to be about 2,000 kilocalories per capita per day, or 0.1 kilowatt per capita in average power provided (80 percent for cooking and 20 percent for electricity; Reddy, 1999). The cooking needs of the 2 billion people not served by modern fuels correspond to about 120 million tonnes of oil equivalent of LPG a year-which equals 1 percent of global commercial energy consumption or 3 percent of global oil consumption. This is less than is currently lost flaring natural gas in oil fields and refineries.

Thus commercial energy requirements for satisfying basic needs in rural areas are truly modest. Yet provision of even these modest amounts of energy to rural areas would offer the potential for enormous increases in amenities, particularly if these modern energy carriers were coupled with energy-efficient end-use devices.[3]

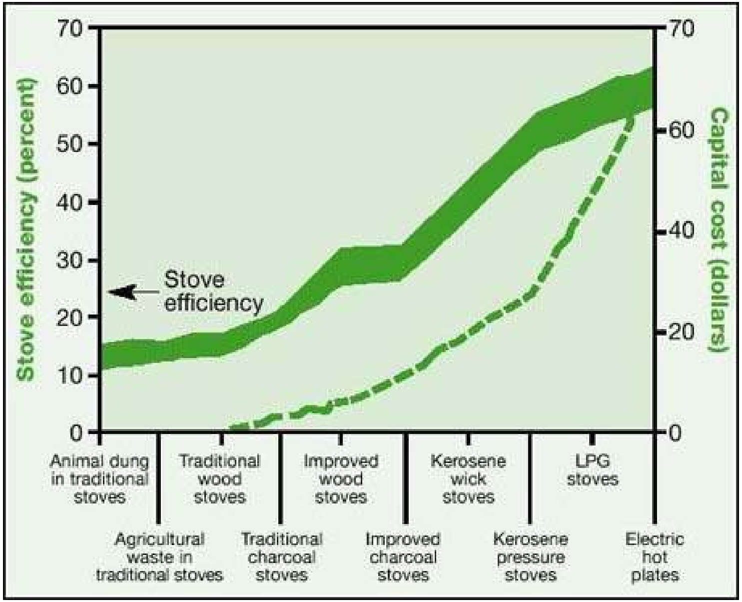

FIGURE 10.1. EFFICIENCY OF STOVES WITH COMMERCIAL AND NON-COMMERCIAL FUELS

Source: Baldwin, 1987.

Progress in delivering modern energy to rural areas has been slow. But as will be shown, technical options to provide rural people with access to convenient, affordable energy services are commercially available (or nearly so). This is particularly the case in regions where modern energy

carriers, such as biogas or producer gas, can be derived from local biomass and where gathering biomass feed-stock can provide opportunity for income generation. The challenge of making modern energy available to the very poorest households is primarily institutional, notwithstanding the economic costs and risks inherent in developing and disseminating untried systems. New financial mechanisms and other innovative policy approaches are needed, as discussed below.

Fuels in rural areas: climbing the energy ladder

The oldest human energy technology, the home cooking fire, persists as the most prevalent fuel-using technology in the world. For much of the world's population, household fuel demand makes up more than half of total energy demand. The energy ladder (discussed briefly above and in chapter 3) is used here as a framework for examining the trends and impacts of household fuel use. As figure 10.1 illustrates, the fuel-stove combinations that represent rungs on the ladder tend to increase in cleanliness, efficiency, and controllability. Conversely, capital cost and dependence on centralised fuel cycles also tend to increase with movement up the ladder.

Shortages of local wood supplies combined with institutional and economic constraints on petroleum-based fuels often lead to household coal use, which is widespread in Eastern Europe, China, and South Africa.

Coal has a higher energy density than wood and so is easier to store. Coal's high energy density also makes it cost-effective to ship over longer distances than wood to efficiently supply urban or rural markets. In these senses, coal is similar to other household fossil fuels. Unlike kerosene and gas, however, coal often represents a decrease in cleanliness relative to wood. Like wood, another solid fuel, coal is difficult to use efficiently in household appliances.

BOX 10.1. COMPARISON OF STOVE PROGRAMMES IN CHINA AND INDIA	
China	**India**
The programme focused on areas with the greatest need and selected pilot counties with biomass fuel deficits.	The programme was implemented country-wide, resulting in dispersion of effort and dilution of financial resources.
Direct contracts between the central government and the county bypassed much bureaucracy. This arrangement generated self-sustaining rural energy companies that manufacture, install, and service stoves and other energy technologies.	The programme administration was cumbersome, moving from the centre to the state level, then to the district, and finally to the *taluka,* where the stove programme is just one of many national efforts being implemented locally by the same people.
Local rural energy offices run by provincial governments are in charge of	Lack of a strong monitoring plan was a severe weakness in early programmes.

technical training, service, implementation, and monitoring for the programmes. These efforts are separately funded and relatively independent.	Some improvement has occurred through assignment of the task to university-based technical backup units. Coverage is still incomplete, however.
Stoves are not only suitable for fuel savings and reduction of household smoke, but also are designed for convenience and attractiveness, highlighting the lessons learned from problems in early programmes that stressed only fuel savings.	India has made a wide variety of attempts to integrate efficiency and convenience, which have suffered from the top-down structure of the programme.
Stove adopters pay the full cost of materials and labour. The government helps producers through stove construction training, administration, and promotion support.	Stove adopters pay about half the cost of stoves; the government pays the rest. As a result the producer's incentive to construct stoves is oriented towards the government.
Emphasis has been on long-lived stoves made of ceramic or metal and otherwise designed to be a significant household asset for a number of years.	Many of the stoves have been made from local materials and by villagers without artisanal skills, resulting in short lifetimes in day-to-day household use.

Source: Smith and others, 1993; Barnes and others, 1993;

Ramakrishna, 1991a, b.

Climbing the energy ladder for cooking can be accomplished using commercially available technologies such as improved cooking stoves and kerosene or LPG. As discussed below, biogas and producer gas are almost at the point of commercialisation, and additional and cleaner advanced technologies for meeting cooking needs are under development.

Improved cooking stoves

Since about 1980, several hundred programmes around the world have focussed on developing and disseminating improved biomass cooking stoves in the villages and urban slums of the developing world. These programmes have ranged in size from the introduction of a few hundred stoves by local non-governmental organisations to huge national efforts in China and India that have affected millions of households. The programmes seek to accelerate the natural trend for people to move towards cleaner, more efficient devices when they are available and affordable.

Such programmes have had mixed success. Some have disseminated many improved stoves with significant lifetimes. Others have not. The failures, however, represent progress along a learning curve, and more recent programmes have tended to have higher success rates. In this regard, it is

instructive to compare the two largest initiatives, those of China and India (box 10.1).

Over the past 20 years, perhaps 90 percent of world-wide installations of improved cooking stoves occurred in China. From 1982-99 the Chinese National Improved Stoves Programme reported the installation of improved stoves in more than 175 million rural households. These were mainly biomass stoves used for cooking. But in the northern states of China, where temperatures drop during the winter, dual-use stoves for cooking and heating were included. In China improved stoves are affordable, and the government contribution is low. An improved stove in China costs about 85 yuan ($10), and the government contributes an average of 4.2 yuan per stove ($0.84). Part of the success of the programme is attributed to the attention-including well-publicised national competitions and awards-given to improved stove design.

The Indian programme, initiated in 1983, is called the National Programme on Improved Chulhas (cooking stoves). So far, nearly 30 million stoves have been disseminated. A mix of portable (without chimneys) and fixed designs have been approved. The government subsidises at least half of the costs of the stoves, which amounts to 200 rupees ($4.50) per stove. Although dissemination has been impressive, follow-up surveys suggest that less than one-third of the improved stoves are still in use. Some reasons given for discontinuing use are that the stoves did not really save

energy, did not eliminate smoke, or broke down. Other surveys found that adopters felt that stoves were consuming less energy and producing less smoke. The mixed perceptions indicate differing levels of success in implementation.

Several lessons can be learned from the two programmes. The greater success in China can be attributed to programme design and implementation, including the factors described in box 10.1. Both programmes now face pressure to reduce subsidies in a more market-based approach. In addition, although both programmes now incorporate monitoring for energy efficiency, neither includes evaluations of the smoke-exposure benefits.

The cooking needs of the 2 billion people not served by modern fuels correspond to about 1 percent of global commercial energy consumption or 3 percent of global oil consumption.

Another commonly cited example of success is the introduction of a more efficient ceramic charcoal cooking stove, the *jiko,* developed in Kenya. At. least 700,000 such stoves are now in use in that country, in more than 50

percent of urban homes and in about 16 percent of rural homes.

About 200 small-scale businesses and artisans produce more than 13,000 stoves each month. Both the stove itself and the general programme for disseminating it have been adapted for use in a number of other African nations (table 10.1).

The process of research, development, demonstration, and commercialisation that led first to the improved jiko and then to other high-efficiency stoves was seeded by international and local development funds (in contrast to the Indian and Chinese programmes, which were almost entirely organised and funded domestically). Most important, policy-makers decided not to directly subsidise the production and dissemination of these stoves but to provide support to designers and manufacturers.

Because the stoves were relatively expensive ($15) and their quality was highly variable, sales were slow at first. But continued research and increased competition among manufacturers and vendors spurred innovations in both the materials used and the methods of production. An extensive marketing network for those stoves is flourishing, and prices have fallen to $1-3, depending on size, design, and quality. This outcome is consistent with the learning curve theory, whereby the price of a new technology decreases by a uniform amount (often about 20 percent) for

each doubling of cumulative sales (chapter 12).

Part of the success of the jiko, however, is due to its use of a relatively high-quality fuel, charcoal. It is much easier to design simple stoves with high energy efficiency for use with such low-volatility solid fuels relative to those that use the unprocessed biomass that is the main source of household energy in the world's villages. Charcoal stoves are also inherently less polluting than those burning unprocessed biomass, and thus do not incorporate chimneys. Like other low-volatility solid fuels-such as some coals-charcoal produces fewer health-damaging particles and gases than wood, but it does produce substantial carbon monoxide. Households relying on such low-volatility fuels, therefore, risk overnight carbon monoxide poisoning, which annually causes thousands of deaths world-wide.

TABLE 10.1. NUMBER OF IMPROVED STOVES DISSEMINATED IN EAST AND SOUTHERN AFRICA, 1995

Country	Urban	Rural	Total
Kenya	600,000	180,000	780,000
Tanzania	54,000	n.a.	54,000
Uganda	52,000	n.a.	52,000
Ethiopia	23,000	22,000	45,000

Rwanda[a]	30,000	n.a.	30,000
Sudan	27,000	1,400	28,400
Zimbabwe	11,000	10,000	21,000
Burundi[a]	20,500	n.a.	20,500
Somalia[a]	15,400	n.a.	15,400

n.a. - Not available. a. Civil strife has significantly affected stove programmes and reduced the number of improved stoves in use.

Source: Karekezi and Ranja, 1997.

In addition, the process of making charcoal from wood is often quite inefficient, leading to heavy pressure on forests in much of Africa to supply urban areas. The inefficiency of charcoal kilns means that the charcoal fuel cycle is probably the most greenhouse-gas-intensive major fuel cycle in the world, even when the wood is harvested renewably, and often it is not. Thus charcoal could not be a sustainable rural energy option in the long run, unless its supply system were to be drastically altered.

Even the best biomass stoves available today do not greatly reduce the health-damaging pollution from biomass combustion, although they may put it outside through well-operating chimneys or hoods. This is certainly

better than releasing the smoke inside; but in densely populated villages and slums, it can lead to heavy neighbourhood pollution. Thus even nearby households using clean (or no!) fuels may suffer from high levels of exposure. Therefore, because of health concerns-unless truly clean-burning biomass stoves can be developed at reasonable costs-in many areas, improved stoves are probably not sustainable in the long run. They may continue to play an important interim role in improving the quality of life of the rural and urban poor; but as concluded in chapter 3, the long-term goal should be to eliminate household use of unprocessed solid fuels.

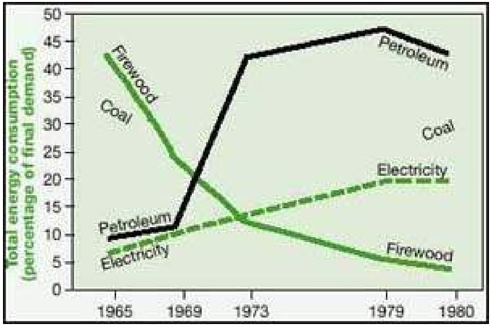

FIGURE 10.2. POST-BIOMASS ENERGY TRANSITION IN THE REPUBLIC OF KOREA, 1965-80

Source: Baldwin, 1987.

Kerosene and LPG actually produce

Kerosene and LPG actually produce fewer greenhouse gas emissions per unit of energy service than biomass fuels used in traditional ways.

Kerosene and liquefied petroleum gas

In countries that achieved successful rural development during the past 50 years, kerosene and then LPG replaced biomass fuels. Figure 10.2 shows the changing household fuel picture in the Republic of Korea as rural development proceeded in the 1960s. At the start of the period, wood was the chief fuel, but 15 years later it had been replaced almost entirely by petroleum-based fuels. Similar transitions have occurred in other regions as well. Natural gas and town gas (made from coal) have continuing important roles in urban development (but rarely in rural areas, because of pipeline transmission requirements).

As consumers climb the energy ladder, kerosene is usually the first modern fuel to be used, because it is more easily transported and stored than LPG. However some countries-notably China-have restricted the availability of kerosene, thereby encouraging the direct movement to LPG. Kerosene, although substantially superior to biomass in efficiency and cleanliness, is not as desirable as LPG, which burns nearly without pollution in comparison with fuels on lower rungs. Of course, liquid and gaseous fuels

pose other risks: For LPG, the most important are fires and explosions; in the case of kerosene, children may suffer poisoning due to careless household storage. Experience has shown, however, that these risks are lower than those posed by biomass fuels.

LPG must be distributed in pressurised canisters that, along with the stove, involve significant up-front investments by households. In addition, both LPG and kerosene require a stable, reliable distribution system running from the refinery to neighbourhood distributors, something that does not exist in many parts of the developing world. The combination of these two factors often prevents LPG from being used by many households that could otherwise afford its daily cost. Indeed, in many developing-country cities, the daily cost of LPG would be less than the cost of shipping biomass from rural areas. Lack of capital for the stove and canister and poor supply reliability, however, prevent households from shifting to LPG.

Despite these problems, LPG programmes have been very successful in most of Latin America, particularly in Brazil, where LPG has replaced all other fuels for cooking-even in many remote rural areas. The main reason for this success was a very dependable system of distribution and replacement of LPG canisters.

A study in Hyderabad, India, found that the simple measure of stabilising LPG supplies by the local government encouraged many urban households

to shift to LPG. This is a policy without fuel subsidies that saves money for households and has a beneficial impact on the environment (Barnes and others, 1994). If users have a first-cost constraint, the programme should provide low-interest loans towards initial costs. Subsidies to help households meet the up-front costs for equipment such as stoves and canisters are much more acceptable policies than subsidising fuel. Fuel subsidies alone tend to divert use of fuel to industry, transport, and households that already have stoves, making the subsidies very costly, economically inefficient ways to help the poor.

Because fossil fuels such as kerosene and LPG are non-renewable and their combustion contributes to greenhouse-gas emissions, some may question their role in sustainable energy strategies. However, the quantity of LPG needed to support cooking for the current unserved population of 2 billion is trivial at the global level (see above). Moreover, kerosene and LPG actually produce fewer greenhouse gas emissions per unit of energy service than biomass fuels used in traditional ways (chapter 3).

Nevertheless, instead of relying on fossil fuels with substantial new infrastructure requirements, it is sometimes desirable to produce clean fuels that can be used efficiently from local biomass resources. Biogas and producer gas systems, as well as advanced technology options such as synthetic LPG or dimethyl ether (DME), appear promising in the longer term.

Biogas for cooking

Biogas, a clean-burning methane-rich fuel gas produced through anaerobic digestion (bacterial action in a tank without air) of suitable biomass feedstocks, is the only biomass-derived modern energy carrier for household applications with which there is widespread experience. Biogas can be generated from cattle dung and animal wastes, and with substantially more difficulty, from some crop residues. Although these feedstocks are frequently used directly as cooking fuel, in most areas they are not preferred fuels and are used only when wood is not available. Biogas systems offer multiple benefits. The digester-effluent is usually a good fertiliser, and, if connected to latrines, biogas plants can provide valuable sanitation services. For cooking and other thermal household tasks, it is simple and reasonably efficient to use the gas directly in conventional low-pressure gas burners. Biogas can also provide lighting when used in mantle lamps.

In societies where suitable feedstocks are readily available, small family-sized biogas digesters were thought to have considerable potential. A number of countries initiated programmes-China and India on a large scale. Results have been mixed, especially in the early stages. China's efforts resulted in the construction of 7 million household-scale digesters from 1973-78. But quality control and management problems resulted in a large number of failures. More recently, coordinated efforts have focused

on regions thought to be most promising for the technology. Service organisations and biogas services stations have been established. By 1994, 5 million domestic plants were operating satisfactorily. India's experience has been on a slightly smaller scale, but the numbers are still impressive- by the end of 1998, almost 2.8 million domestic plants were installed. India's Ministry of Non-Conventional Energy Sources has identified a potential for 12 million digesters.

Biogas experience in Africa has been on a far smaller scale and has been generally disappointing at the household level. The capital cost, maintenance, and management support required have been higher than expected. Moreover, under subsistence agriculture, access to cattle dung and to water that must be mixed with slurry has been more of an obstacle than expected. However, possibilities are better where farming is done with more actively managed livestock and where dung supply is abundant- as in rearing feedlot-based livestock.

BOX 10.2. BIOGAS IN NEPAL

The principal objective of the Biogas Support Programme in Nepal is to promote the wide-scale use of biogas as a substitute for the wood, agricultural residues, animal dung, and kerosene that presently meet the cooking and lighting needs of most rural households in the country. The rising demand for locally available biomass from a rapidly increasing population has helped accelerate the rates of deforestation, soil degradation, and environmental decline in densely inhabited areas. In addition, use of biomass fuels and kerosene has compromised health and welfare-especially of women and children, who are most often subjected to the smoke and fumes associated with the use of these fuels.

Since its inception, the programme has installed more than 40,000 family-size biogas units benefiting more than 200,000 members of rural households. The programme's target is to install an additional 100,000 units by the middle of 2003. This compares to only 6,000 biogas units installed before the programme. This substantial increase has been achieved while simultaneously reducing the costs and increasing the reliability and efficiency of biogas plants.

A critical element in developing the commercial market for these plants has been the programme's innovative financial engineering and judicious application of consumer subsidies. The subsidy, fixed at three levels, accounted for 35 percent of the total cost of biogas plants in 1998. The objective of the programme is to eliminate dependency on direct subsidies by 2003. The programme has also strengthened institutional support for the biogas market.

At the start of the programme, essentially only one state-owned company, the Gobar Gas Company, was producing biogas plants. By the end of 1998, as a direct result of market development, 38 private companies besides Gobar had entered the business. To be eligible to receive the subsidy provided to farmers, all participating companies must meet strict production quality and service standards for their plants. As a result of the growing competition, technical design modifications, and better quality control measures, the overall cost of biogas plants in Nepal has declined by more than 30 percent since 1992. In addition to the institutional improvements, employment for skilled as well as unskilled labour in rural areas has been generated.

Source: Mendis, 1999.

The initial enthusiasm for biogas has thus been somewhat dampened by experience. Because of its requirement for relatively large amounts of animal dung, the niche for household biogas plants is likely to remain small. Poor families do not have access to enough dung, and better-off families with sufficient animals often prefer to purchase fuel and fertiliser rather than spend time gathering dung and managing the often-temperamental digesters. Even so, in the right social and institutional context, and with appropriate technical expertise, the potential for biogas remains significant. These conditions seem to have been achieved in the Biogas Support Programme in Nepal through an innovative financial scheme (box 10.2).

Producer gas for cooking

An alternative to biogas is producer gas, a mixture consisting largely of carbon monoxide, hydrogen, and nitrogen. Producer gas is generated in a

thermochemical conversion process through partial oxidation in air of biomass feedstocks (Stassen, 1995). The basic principles of generating producer gas have been known since the 18th century. Producer gas derived from biomass has been used for domestic and industrial heating purposes, for cooking, for stationary power, and for motor vehicle applications. (During World War II more than a million gasifier-powered vehicles helped to keep basic transport systems running in Europe and Asia.)

During periods of peace and wide availability of cheap, more convenient fossil fuels, interest in biomass-derived producer gas has been low. The energy crises of the 1970s rekindled interest in producer gas technology, but interest waned again with the collapse of world oil prices in the mid-1980s. Once again, there is growing interest in technology for making producer gas from biomass for cooking, heating, and electricity generation. Power generation applications of producer gas are discussed later in this chapter. Here the focus is on domestic cooking.

Part of the reason for renewed interest in producer gas technology is increasing concern about the adverse health effects of indoor air pollution caused by biomass and coal burned for domestic cooking and heating (chapter 3) and the large role that producer gas used in gas-burning stoves could play in reducing this pollution-the air pollution from these stoves is nearly zero. In typical agricultural regions, the energy generation

potential from producer gas is greater than that from biogas, because crop residues tend to be more abundant than dung.[4] And whereas biogas generation is often the preferred energy conversion technology for making use of the energy content of dung, producer gas generation is a far easier approach for exploiting the energy content of crop residues.

In addition, because it is a chemical rather than biological process, producer gas manufacture is not sensitive to ambient temperature, greatly increasing the potential geographic extent of its application. Another reason for renewed interest in biomass-derived producer gas in China is a severe new air pollution problem caused by the burning of crop residues in fields-a consequence of the rising affluence of farmers (see the annex to this chapter). This problem is forcing a search for new productive uses of crop residues.

Several Chinese provinces are making efforts to convert residues into producer gas in centralised village-scale gasifiers and to distribute the cooking gas by pipes to households. For example, the Shangdong Academy of Sciences has developed crop residue gasifiers and centralised households meet equipment such gas supply system technology for are much cooking gas applications, and 20 such policies village-scale gasification systems are operating in the province (Dai and Lu, fuel. 1998). Monitoring and assessment of a village experience in Shangdong Province (case 1 in the annex) shows that current technology has considerable

consumer appeal and would be highly competitive if the gas were properly priced. The technology for making producer gas from crop residues promises to be widely deployable for cooking applications, and thus to largely solve the indoor air pollution problem caused by stoves that burn biomass or coal.

TABLE 10.2. GLOBAL POPULATION AND ACCESS TO ELECTRICITY, 1970-90 (MILLIONS OF PEOPLE)

Country	1970	1980	1990
World population	3,600	4,400	5,300
Rural population	2,600	3.000	3,200
With access to electricity[a]	610	1,000	1,400
Without access to electricity	2,000	2,000	1,800
Percentage of rural population with access	23	33	44

a. Access includes people living in villages connected to power lines. This does not necessarily mean that most households are hooked up to electricity.

Source: Davis, 1995.

Subsidies to help households meet

Subsidies to help households meet the up-front costs for equipment such as stoves and canisters are much more acceptable policies than subsidising fuel.

One problem posed by current gasifiers used in China is that they produce substantial tars (condensable hydrocarbons that are scrubbed from the gas before delivery to consumers). If disposed of without adequate treatment to groundwater or surface water, these tar wastes would pose significant water pollution problems. Moreover, the option of using crop residues or producer gas for cooking will not solve the air pollution problem in China that arises from burning excess crop residues in the field. The producer gas option is about twice as efficient as direct combustion in providing cooking services, so that only about half as much residue is required for cooking relative to direct-combustion stove systems.[5] At the national level, use of just 60 percent of all crop residues potentially available for energy purposes would be adequate to meet all rural cooking needs.

In addition, the producer gas cooking option poses another public health risk: Typically, about 20 percent of producer gas is carbon monoxide-of which accidental leaks into houses can be lethal. Although some hydrocarbon impurities in the gas impart an odour to producer gas that is usually noticed before a lethal dose is inhaled, occasional accidents are

inevitable. Therefore (as discussed below), safe, clean, advanced technological options for producing cooking fuel from biomass should be the focus of research and development.

Rural electrification

Electricity is at the top of the energy ladder and is highly efficient and convenient for some specialised cooking appliances, such as rice cookers and microwave ovens. But for many years to come, electricity is unlikely to be practical for general cooking in most rural areas of the developing world. Nevertheless, for lighting, communication, refrigeration, and motor applications, electricity is essential for a satisfactory quality of life. Moreover, electricity is key to improving agricultural productivity through mechanisation and is essential for many rural industrial activities. Considerable progress has been made in rural electrification programmes designed to extend electricity services to isolated villages (table 10.2).

The centralised approach

Between 1970 and 1990, 800 million people in rural areas gained access to electricity. Yet of the 3 billion people living in rural areas of developing countries in 1990, 2 billion were still without access to electricity. This global total masks significant variations between regions and countries. In particular, China's rapid electrification programme-through which 365

million rural residents gained access to electricity from 1970-90-significantly increased the world total. If China were excluded, current access levels would drop from 44 to 33 percent, or exactly the level of 1980.[6]

The distinction between access to electricity by villages and households should also be noted. India, for example, has an ambitious rural electrification programme, targeting agricultural end use. But while 80 percent of villages have electricity, less than 50 percent of households can afford it.

Several studies highlight an important point for economic success: electrification cannot by itself ensure economic development. It is a necessary but insufficient condition. Electrification works best when overall conditions are right for rural income growth and when it is complemented by social and economic infrastructure development-such as rural water supplies, health programmes, primary and secondary education, and regional and feeder roads. Thus rural electrification contributes to but is not a substitute for other rural development measures.

Rural electrification programmes have typically concentrated on connecting villages and remote areas to a national grid-often owned and operated by a public utility. The tendency has been to extend the grid

incrementally, reaching towns and settlements in order of increasing capital costs. Thus remote areas with small populations are likely to be the last to receive electricity. Moreover, many rural areas face high transmission and distribution costs, for several reasons:

- **The capacity of power lines is inefficiently used because of low population.**

- **Densities and demand levels are low.**

- **Villages may have very peaky (undiversified) demand profiles. Line losses tend to be high.**

- **In addition, incremental extension of the grid (rather than extension optimised to minimise losses) causes lines to be strung haphazardly, resulting in greater losses.**

The decentralised approach

Because of the problems of supplying grid electricity for small, scattered, peaky loads, decentralised electricity generation is becoming more attractive. With decentralised systems, the high costs of transmission and distribution networks can be avoided. But small-scale, decentralised solutions face other barriers. The decentralised generation technologies discussed below are diesel-engine generator sets, small-scale hydropower,

photovoltaics, wind, and small-scale biopower using producer gas. No attempt is made to be comprehensive on the technological opportunities for decentralised electricity generation. Instead, the discussion illustrates key features of different technologies, highlighting advantages and drawbacks for rural development needs.

Diesel-engine generator sets. Diesel generators are common in many remote settlements, either for a single user or as part of a local distribution network. Such systems may be operated by a power utility or, more commonly, by private enterprises. Rural hospitals, government offices, and police stations in remote areas typically have their own diesel generators.

Diesel sets with capacities of 50-500 kilowatts of electricity are widely used in rural Latin America and Asia but have only recently been disseminated in Africa. The electricity produced by diesel sets typically costs $0.30 a kilowatt-hour-two to three times the cost of electricity from grids in urban areas but still cost-effective relative to grid extension. (This cost is typical of the Amazonia region of Brazil, where there are 900 diesel sets with a total generating capacity of 391 megawatts.) The high costs of maintenance and of transporting diesel fuel and lubricating oil to remote places make electricity fairly expensive.[7] Despite these costs, electricity is typically highly valued by local populations because of the enormous improvements in living standards that it brings (box 10.3). But while high-

cost electricity may be acceptable for satisfying basic needs in households and for some agricultural and cottage industry applications, lower costs are needed to attract a greater job-generating industrial base to rural areas.

Small-scale hydropower. Small-scale hydropower is a locally available resource that in some regions can be exploited to deliver electricity or mechanical power (for pumping water and other applications) to rural areas. The resource potential for small-scale hydropower is discussed in chapter 5; its technology, costs, and future prospects are discussed in chapter 7. Here the focus is on current activities and the prospects for using small-scale hydropower to address rural development needs.

Small-scale hydropower technology, which is being pursued in about 100 countries, is often divided into three categories: micro hydro (less than 100 kilowatts), mini hydro (100-1,000 kilowatts), and small hydro (1-30 megawatts). By the end of 1994 China alone had 6,000 small-scale hydropower stations with a total installed capacity of 15,650 megawatts, supplying 49 terawatt-hours of electricity (Qui and others, 1996)-29 percent of hydroelectric power generation and nearly 8 percent of rural electricity consumption (Deng and others, 1996). In 1989 China accounted for about 38 percent of world-wide small hydropower (23.5 gigawatts), at which time more than 130 companies manufactured equipment specifically for plants with capacities ranging from 10 kilowatts to more than 10

megawatts. Of the 205 turbines ordered world-wide in 1989, the size distribution was micro hydro, 15 percent; mini hydro, 57 percent; and small hydro, 28 percent (Moreira and Poole, 1993). In China and Viet Nam even sub-kilowatt systems have been sold for household electrification. Such turbines are installed at the end of hose-pipes, with somewhat unreliable but serviceable results. However, the potential market for such systems is limited by the availability of water resources.

On a somewhat larger scale, hydropower plants of 50 kilowatts and more can be used to electrify communities or small regions by establishing mini grids. Costs are highly variable (chapter 7), depending on the site topography, proximity of the site to the main load area, and hydrological conditions.

Small-scale hydropower has one drawback: it is almost always obtained from run-of-river plants that lack the reservoir capacity to store water. Consequently, severe seasonal variations in power output may occur, depending on a site's hydrology. Thus the long-term viability of small-scale hydropower may depend on backup electricity that is supplied either locally or through the grid (Moreira and Poole, 1993).

Photovoltaics. Photovoltaic technology is cost-effective in providing electricity to rural areas at the very smallest scales (typically less than 100 watts) in areas with no access to grid electricity and where electricity

demand is characterised by such low levels and infrequency that even diesel electricity cannot compete (see chapter 7 for details about photovoltaic technology and its economics in such applications). The potential for photovoltaic technology to support rural development arises from the fact that it can be used for household lighting, radios, and television sets, and to refrigerate medicines at rural clinics.

In 1999 global photovoltaic sales totalled 200 megawatts, 10 percent of which was for off-grid applications in rural areas of developing countries. One important obstacle to wider rural deployment of photovoltaic technology is the limited financing available for such small systems (see section below on the time horizon for technological options). Kenya has the world's highest penetration rate of household photovoltaic systems, with more than 80,000 systems in place and annual sales of 20,000 systems. Fifty local and fifteen international importers, assemblers, installers, and after-sales providers serve this market, which developed without significant aid, subsidies, or other support. Although the current market is strong, there is still a tremendous need to standardise equipment, as well as improve batteries, lighting fixtures, and electronic ballasts used in integrated household photovoltaic systems. In addition, possible credit arrangements need to be studied, as do the relative advantages of leasing a system rather than purchasing it.

In 1999 South Africa's power utility, Eskom, entered into a joint venture

with Shell Solar Systems to provide 50,000 homes with photo-voltaic systems in areas where grid connection is not considered feasible. This three-year programme contributes to a market that is believed to exceed 2 million households. Customers pay a monthly rate to lease and use the equipment, which allows a reasonable rate of return to Eskom.

BOX 10.3. DIESEL ENGINES IN A MULTIPURPOSE PLATFORM PROJECT IN MALI

In Mali a project is under way to introduce, by 2003, 450 multipurpose platforms to provide, at the village scale, mechanical power and electricity through diesel engines to 10 percent of the country's rural population. At least two-thirds of these platforms will be coupled to water and electricity distribution networks. By 2003 rural access to electricity is expected to be more than 3 percentage points higher than urban access. Although the project is based on the use of diesel fuel oil, it is envisaged that in the future pourghere nut oil or some other liquid biofuel will be used.

The engine selected for this project is a 1950s-vintage slow diesel engine (a Lister engine, from India). This engine was chosen because of its low initial capital cost; low prices for its spare parts; its ability to operate without damage on the relatively low-quality diesel fuel typically available in villages; its ease of operation, maintenance, and repair by local artisans (blacksmiths, mechanics, carpenters); and the availability of a network of sellers and servicers for it throughout much of Mali.

It is intended that the engine in a typical platform would power various types of equipment, such as a cereal mill, husker, alternator, battery charger, pump, welder, and carpentry machine. Thus the platforms would reduce many rural women's burdensome tasks (fetching water, grinding cereal); offer them income-generating opportunities and management experience; and, as they become more economically independent, help them improve their social status. Because so many activities would be supported by the platforms, their economic and social benefits would be felt at multiple levels, resulting in an overall empowerment of women. In the pilot phase of the project (1996-98), during which 45 platforms with 14 water or electricity networks were installed, the platforms' availability stimulated the creation, development, and modernisation of artisanal activities in participating villages. The platforms are being operated and maintained on a cost-recovery basis by private enterprise.

By design, the acquisition of a multipurpose platform is a demand-driven process. The initial request has to be made by a recognised, registered women's association at the grassroots level. International donors are subsidising equipment costs (including the engine, mill, de-huller, alternator, battery charger, and building) at up to $1,500 per module. In situations where the supply of electricity and running water is requested, the contribution of the international donor can be increased by up to $10,000 per module. An equity contribution of at least 50 percent is required of the women's associations. Operation and maintenance costs are borne entirely by beneficiaries.

The mechanical work provided by the engines costs about $0.25 per kilowatt-hour (see table). Notably, more than 70 percent of the cost is for diesel fuel and lubricating oil, which must be imported into the region. If the mechanical work were converted to electricity, the added cost associated with the generator and conversion losses would increase the electricity cost to at least $0.30 per kilowatt-hour. If liquid biofuels produced in the region eventually could be substituted for imported oil, the region's balance of payments would be improved, although costs would probably not be reduced much or at all, because liquid biofuels tend to be more costly than petroleum fuels.

Although this project is interesting in revealing consumer wants, it is in its initial phase of implementation, and only experience will supply information on real costs. Nevertheless, the project shows that there are attractive alternatives to grid extension, that rural electrification does not necessarily mean grid electrification, that decentralised electrification is a serious option, and that entrepreneur-driven participatory development is crucial.

Cost of mechanical work for a diesel engine, Mali multipurpose platform

Cost	Dollars per year	Dollars per kilowatt- hour
Capital[a]	131	0.018
Fuel[b]	1,140	0.138
Maintenance		

Maintenance		
Every 100 hours		
Lubricating oil	158	0.022
Other	36	0.005
Every 500 hours	179	0.025
Every 1,000 hours	104	0.015
Every 1,500 hours	74	0.010
Total	1,820	0.233

a. For an 8-horsepower (6-kilowatt) Indian Lister diesel engine with a 7-year plant life costing $600 (excluding the cost of a generator) and operated 1,500 hours a year at 80 percent of rated capacity, on average, so that the annual average capacity factor is 13.7 percent. Assuming a 12 percent discount rate, the capital recovery factor is 21.9 percent a year.

b. For a diesel fuel price of $0.44 a litre and an engine efficiency of 30 percent (higher heating value basis).

Source: Mali and UNDP, 1999.

Still another approach to reach a greater portion of low-income rural people was adopted by Soluz. This company developed a system to lease small photovoltaic battery systems to provide high-quality electric services

at an affordable price while offering a positive financial return to its investors. In 1993, with assistance from the Rockefeller Foundation, Soluz conducted a pre-feasibility study for a solar electricity delivery company and construction of a company prototype for 200 rural homes in the Dominican Republic. The company installs standalone photovoltaic battery systems on or near rural homes yet retains ownership of the systems. The photovoltaic systems provide lighting and access to information services (through radio and television). Users make regular payments, as determined in the lease agreement, and the company is responsible for maintaining the systems.

In Central America customers pay a monthly fee of $15-20, depending on the size of the photovoltaic system leased. The company has an on-time collection rate exceeding 90 percent. Many customers are small businesses, for whom the provision of high-quality energy services contributes to increased profitability.

But even where appropriate financing is made available, the poorest households often cannot afford photovoltaic systems (box 10.4). In considering measures to support photovoltaic programmes for rural areas, it is important to pay particular attention to the poorest households and to strategies to make the technology available to them.

Although significant in improving the quality of life in rural areas, without

major cost reductions, photovoltaic technology will be limited mainly to remote household and other small-scale applications and will not be able to compete in the provision of electricity for manufacturing or even most cottage industrial applications.

BOX 10.4. EQUITY ISSUES RELATING TO PHOTOVOLTAIC TECHNOLOGY FOR RURAL AREAS IN INDIA

Of the 79 million rural households in India without electricity (out of a total of 114 million rural households), 7, 17, and 75 percent of households could afford, respectively, 37-watt (four-light), 20-watt (two-light), and 10-watt (one-light) photovoltaic systems with Grameen-type financing (five-year loans at 12 percent interest with a 15 percent down payment; see box 10.7). Thus it appears that the poorest 25 percent of households cannot afford any photovoltaic purchase, even with financing.

But such findings, which are based on willingness-to-pay considerations, might be overly simplistic. The availability of lighting might be exploited to earn extra income that could make a photo-voltaic system affordable for even the poorest household. If, for example, a poor Indian household could weave two extra baskets a night by the light made available by a 10-watt photovoltaic system, the technology would become affordable.

Source: Reddy, 1999; Hande, 1999.

Household-scale wind turbines (of about 100 watts) offer benefits to wind-rich regions similar to those offered by domestic photovoltaic systems.

Wind. There are two promising ways to exploit wind power to meet rural energy needs. The first is household units that provide electricity at. scales where neither grid power nor mini-grid power from diesel units is cost-effective. The second is village-scale wind-battery-diesel hybrid systems (using wind turbines with capacities typically of 5-100 kilowatts).

Household-scale wind turbines (of about 100 watts) offer benefits to wind-rich regions similar to those offered by domestic photovoltaic systems. Such turbines have been developed, produced, and deployed, for example, in China, mostly in the Inner Mongolian Autonomous Region. The dispersion of houses in this region of low population density (18 people per square kilometre) makes household wind systems a viable option for providing electricity. In Inner Mongolia an estimated 130,000 small-scale (mostly 50-200 watt) wind energy systems have been installed, providing electricity for lighting, radios, television, and small appliances to more than 500,000 people, mostly rural herdsmen (about one-third of the population). About 89,000 of these systems are operating routinely,

producing from 8.7 megawatts of installed capacity about 15.7 gigawatt-hours a year (Wu, 1995).

The success of the Chinese programme was achieved through careful planning and the creation of an effective regional and local infrastructure for manufacturing, sales, maintenance, and training. This included the development of a market for individual household systems through various subsidy mechanisms. The government of Inner Mongolia also recognised and allowed for the long gestation period and sustained support needed to create a thriving local industry. The project has also led to technology transfers at many levels-between Inner Mongolia and local, regional, and national organisations within China, as well as with other countries. Replicating the programme would require enough institutional capacity to support such ventures.

Where rural households are clustered in villages far from electric grids that are served instead by diesel-engine generator sets, an alternative option is to deploy wind turbines in wind-diesel or wind-battery-diesel hybrid configurations, which have been installed in many parts of the world (Baring-Gould and others, 1999). In regions where diesel fuel is costly, these hybrid systems can lead to lower electricity costs and less air pollution than conventional diesel-engine generator sets.

Unlike the household-scale wind turbines being developed in China,

however, many components of these hybrid systems are based on technology developed in industrialised countries, and costs of imported systems are often prohibitive. But if these systems can be mass produced in developing countries under arrangements-such as international industrial joint ventures-that are conducive to technology transfer, substantial cost reductions are possible (see chapter 7 for an example).

Small-scale biopower using producer gas. Biomass-derived producer gas (see above) can be used to make electricity at scales comparable to those associated with diesel-engine generator sets. The potential benefits are:

- **The capacity to use locally available biomass as fuel instead of oil imported into the region.**
- **Lower electricity generation costs than with diesel.**
- **Increased rural income generation, and possibly rural industrialisation, as a result of the lower electricity cost.**

The reciprocating compression-ignition (diesel) engine is the main commercially viable engine available for these applications.[8] When producer gas is used with such engines, it must be supplemented with a pilot oil to assist ignition because mixtures of producer gas and air do not auto-ignite at the pressures and temperatures realised when the gas is

compressed. As a result producer gas can typically displace about 70 percent of diesel fuel consumption. When operated with producer gas in the dual-fuel mode, diesel-engine generators have somewhat lower efficiencies and rated capacities (typically about 20 percent lower than when operating on pure diesel fuel).

Producer gas must meet far higher standards for reciprocating engine operation than for cooking or heating (domestic or industrial) applications. The main problem is the propensity of tars formed in the gasifier to condense on downstream surfaces, causing problems such as the sticking of engine gas intake valves. Most early gasifiers generated so much tar that adequate gas clean-up for engine operation was impractical, and tar removal would significantly reduce the potential for power generation from a given amount of biomass feedstock. But in recent years, gasifiers have been developed (notably in India) that generate tars at levels that make engine operation on producer gas acceptable (Kartha and Larson, 2000).

Biomass-derived technology for producer gas, reciprocating-engine generators is commercially ready. In India, for example, the Ministry of Non-Conventional Energy Sources has supported development efforts that have led to technically sound gasifier-engine systems and trial implementation of more than 1,600 such systems with a total installed capacity of more than 28 megawatts (Kartha and Larson, 2000). For

engines operated on producer gas and pilot oil, fuel costs are typically much lower than for conventional diesel systems. But capital, operation, and maintenance costs are higher (see table A10.1).

In fact, the savings derived from diesel replacement have to pay for the extra initial capital cost as well as the extra operation and maintenance costs incurred for the gasifier. The technology can be cost-effective, either where diesel fuel costs are very high (for example, $0.35-0.40 a litre or more, as is often the case for extremely remote regions) or, with efficient capital utilisation, in regions where diesel fuel prices are more moderate. If the diesel fuel price is $0.25 a litre, a typical system must be operated at full capacity for 3,000 hours a year to break even with a conventional diesel system. About 6,000 hours of annual operation are needed to realise a cost savings of 25 percent (see table A10.1). It is desirable to seek opportunities for such high rates of capacity utilisation because consumers are likely to be more motivated to adopt the technology if they can realise substantial cost savings. Unfortunately, achieving high rates of capital utilisation is often difficult because local electricity. demand is typically low and sporadic but peaky, with very little electric load diversity.

Historically, electric utilities have discouraged independent power producers from selling electricity into grids, but this situation is changing as electricity markets

are becoming more competitive.

A promising strategy for launching a producer gas, engine-generator technology industry would be to focus initially on market opportunities where the technology could be deployed in large numbers in baseload configurations. This requires that two conditions be satisfied. Biomass supplies have to be adequate for fuelling baseload plants, and the demand for electricity has to be adequate to justify baseload operation. Strong candidate regions for doing this are agricultural regions of China where crop residues are abundant and where grid connections exist (87 percent of the rural population in China is grid-connected), so that electricity generated in excess of local needs can be sold into the grid (Li, Bai, and Overend, 1998). Historically, electric utilities have discouraged independent power producers from selling electricity into grids, but this situation is changing as electricity markets are becoming more competitive (chapter 12).

New technologies that might be commercialised in the near term (5-10 years) offer the potential for electricity generation at costs significantly lower than with current technology. One promising new technology is the microturbine, which might be deployed with essentially the same gasifiers that have been developed to provide producer gas for use with diesel dual-fuel engine generator sets.

Microturbines are gas turbines designed for operation at scales of 50-250 kilowatts of electricity, with electric efficiencies (lower heating value) of 25-30 percent for larger units. Microturbines were originally developed for military and aerospace applications and are now offered by several companies for applications in distributed power and cogeneration markets, mainly for use with natural gas or diesel fuel. Developers expect microturbine use to grow rapidly for such applications in regions where there is competition in electricity markets (chapter 8). The technology appears to be readily adaptable for use with biomass-derived producer gas (Henderick, 2000).

Microturbines are less complex (some variants have only one moving part) than reciprocating engines. They can be fuelled with producer gas without de-rating and without loss of efficiency relative to operation on natural gas or diesel fuel. Most important, they need no costly pilot oil (Henderick, 2000). In regions where crop residues or other low-cost biomass feedstocks are readily available, there are reasonably good prospects that the technology could become widely competitive in grid-connected applications (Henderick and Williams, 2000). Case 2 in the annex describes a potential application of the technology to the trigeneration of cooking gas, electricity, and space heating through district heating in a hypothetical village in northern China.

To illustrate the aggregate potential of this technology, consider that in

China, 376 million tonnes of crop residues a year are potentially available for energy purposes.[9] Committing these residues to trigeneration (case 2 in the annex) could provide enough cooking gas for 230 million people (27 percent of China's rural population) plus 270 terawatt-hours a year of electricity (equivalent to 30 percent of coal power generation in China in 1997) plus hot water for space heating in regions where it is needed (for example, in regions with cold winters).

Several public policy initiatives could facilitate the creation of a viable industry for small-scale biopower technologies. One important measure would be to eliminate or phase out diesel fuel subsidies that exist in many regions. Another would be market reforms that facilitate the sale of electricity into electric grids, coupled with incentives to encourage the extension of electric grids to more rural areas. Notably, the commercial availability of competitive baseload biopower technology could profoundly influence the economics of extending electric grids to rural areas. In contrast to the poor capacity utilisation (and hence poor economics) of transmission-distribution lines sending electrons from centralised power plants to rural areas, high capacity factors (and thus more favourable economics) could be realised if electrons instead flowed to urban centres from baseload village-scale biopower plants.

Finally, demonstration projects are needed to prove the viability of new technological concepts for biopower. Projects are needed for biopower

systems based on gasification of alternative crop residue feedstocks, for which tar production rates are higher than for wood chips (Henderick and Williams, 2000). Such projects could involve the use of commercially established diesel dual-fuel engine technologies. Demonstrations are also needed of microturbines in producer gas applications. If carried out together with the above institutional reforms, these projects could lead to commercially viable microturbine-based products for biopower applications in the near term (2005-10).

Leapfrogging to new rungs on the energy ladder

The previous sections have shown that existing and near-term energy technologies have great potential for improving the quality of life in rural areas. But advanced technologies have residual problems that might need to be addressed. For instance, fuels such as LPG are highly desirable for cooking, but making LPG widely available requires considerable infrastructure for distribution, and finding ways to make LPG affordable to the poorest households is a major challenge. Moreover, because LPG is derived from petroleum-a commodity for which price swings can be substantial, as recent experience has shown-price spikes are likely to be burdensome for lower-income households that depend on LPG for their cooking needs.

Local manufacture of clean cooking fuels (such as biogas and producer gas

derived from biomass feedstocks) is a strategy for addressing the fuel-infrastructure challenges and price volatility concerns posed by exclusive reliance on LPG. This strategy also provides opportunities for addressing the needs of the very poorest households, because the need to gather typically dispersed biomass feedstocks (such as dung for biogas or crop residues for producer gas) and deliver them to the conversion facility can sometimes make it possible for the poor to monetise their labour and thereby earn income to help pay for these clean cooking fuels (case 2 in the annex).

But today's available gaseous cooking fuel technologies have limitations. Biogas technologies, though well suited for use with dung feedstocks, are not easily applied to crop residues, which tend to be much more abundant. And a persistent concern about producer gas is that it contains carbon monoxide, accidental leaks of which might lead to fatalities. Odourants added to producer gas could greatly reduce the risk of poisoning, but accidents are difficult to avoid completely.

Advanced technologies can make it possible to manufacture synthetic cooking fuels from biomass that are non-toxic as well as clean. A promising approach is to adapt to biomass some of the technologies being developed for fossil fuels-specifically, syngas-based fluid fuels (chapter 8). Strong candidates are synthetic LPG (SLPG) and dimethyl ether (DME), which can be made from any carbonaceous feedstock by catalytic synthesis

from syngas (a gaseous mixture consisting largely of carbon monoxide and hydrogen). SLPG (like petroleum-derived LPG, a mixture of propane and butane) and DME are superclean, non-toxic cooking fuels that are gaseous at ambient conditions but can be stored and delivered to consumers as liquids in moderately pressurised canisters. These fuels can be produced from crop residues or other biomass feedstocks through thermochemical gasification to produce the needed syngas. (Case 3 in the annex discusses the potential offered by such technologies for rural regions of China rich in crop residues.)

In addition to the toxicity advantages offered by SLPG and DME, both fuels could be readily transported in canisters by truck or donkey cart to remote, scattered households. Producer gas, by contrast, is a viable option primarily for villages in which houses are clustered closely enough to make pipe transport economically viable. Thus SLPG and DME extend the scope of the cooking fuel markets that could be served relative to producer gas. DME is also a potentially strong low-polluting synthetic fuel for diesel-engine vehicle applications (chapter 8) and might be used as tractor fuel, thereby facilitating the mechanisation of agriculture.

Neither SLPG nor DME is currently produced for fuel applications, but either fuel derived from biomass feedstocks could probably be brought to market readiness by 2010-15 if there were sufficient market interest and a focused development effort. Because neither SLPG nor DME is currently on

the market anywhere in the world, a shift from the use of current low-quality fuels to either might be described as jumping to entirely new rungs at the top of the energy ladder (technological leapfrogging).

The time horizon for technological options

Chapters 6-8 and this chapter show that there are abundant opportunities for technological change relating to rural energy. Technological change is desirable to the extent that it serves development needs. Rural development planners can help shape the course of technological change for desirable options, taking into account the time horizons required for development and implementation-demanding more of the longer-term options in addressing societal needs. Options that warrant focussed attention in the near term (that is, implementation in the next 5 years) as alternatives to current technology should offer the potential for immediate improvement. For the medium term (5-15 years), planners should emphasise technologies that can potentially achieve dramatic improvements relative to current technology. To the extent that technologies realisable in the medium term fall short of performance consistent with sustainable development goals, policy-makers should also encourage for the long-term (15-30 years) technologies that are fully consistent with sustainable development goals.

It is also wise to have a balanced portfolio with a combination of near-,

medium-, and long-term options, to ensure a continuing flow of improved technologies into rural energy markets. Successes with near-term improvements can help win political support for the development of longer-term options. Some important technological options for rural energy in the near, medium, and long terms are summarised in table 10.3.

Accelerating rural energy development

The preceding sections show that there are many technological opportunities for implementing the goals set forth at the start of this chapter: providing clean liquid or gaseous fuels for cooking and electricity for lighting and other basic household amenities, and making bulk electricity available at low cost for mechanising rural agriculture and promoting rural industrialisation.

Both centralised and decentralised energy technologies and strategies can make contributions to reaching these ends. But new strategies and policies are needed to increase access to these modern energy services and to make modern energy services widely affordable. Coordinated efforts that include the active participation of rural people can accelerate the process.

Integrated rural development

Making modern energy services more readily available is a necessary but insufficient condition for rural development. To be most effective, certain

forms of energy (such as grid-based electricity) should be introduced into rural areas only after, or along with, other development inputs or infrastructure components. To achieve this integration, it is essential that there be horizontal communication among all agencies involved in rural development.

Many rural development activities-agriculture, transport, water supply, education, income generation, health care-have energy requirements. Yet the ministries and departments responsible for these activities rarely coordinate or cooperate with the ministry of energy, or with one another, to arrive at the most rational, integrated solution to their energy needs. Decentralisation of rural energy planning may help achieve this. But optimising the allocation of development resources requires attention at the central government planning level as well. In the many places where integrated rural development has been pursued, the availability of affordable modern energy supplies has proven to be a catalyst for economic and social transformation.

TABLE 10.3. SOME NEAR-, MEDIUM-, AND LONG-TERM TECHNOLOGICAL OPTIONS FOR RURAL ENERGY

Energy source or task	Present	Near term	Medium term	Long term

Source				
Electricity	Grid or no electricity	Natural gas combined cycles, biomass-based generation using gasifiers coupled to internal combustion engines, photovoltaic, small wind, small hydroelectric for applications remote from grids	Biomass-based generation using gasifiers coupled to micro-turbines and integrated gasifier combined cycles, mini grids involving various combinations of photovoltaic, wind, small hydroelectric, batteries	Grid-connected photovoltaic and solar thermal, biomass-based generation using gasifiers coupled to fuel cells and fuel cell/turbine hybrids
Fuel	Wood, charcoal, dung, crop residues	Natural gas, LPG, producer gas, biogas	Syngas, DME	Biomass-derived DME with electricity coproduct
Cogeneration (combined		Internal combustion	Microturbines and integrated gasifier	Fuel cells, fuel

heat and power)		engines, turbines	combined cycles	cell/turbine hybrids
Task				
Cooking	Woodstoves	Improved woodstoves,	Producer gas, natural gas and DME stoves	Electric stoves, catalytic burners
Lighting	Oil and kerosene lamps	Electric lights	Fluorescent and compact fluorescent lamps	Improved fluorescent and compact fluorescent lamps
Motive power	Human and animal powered devices	Internal combustion engines, electric motors	Biofueled prime movers, improved motors	Fuel cells
Process heat	Wood, biomass	Electric furnaces, cogeneration, producer gas, NG/solar thermal furnaces	Induction furnaces, biomass/solar thermal furnaces	Solar thermal furnaces with heat storage

The provision of affordable financial services for rural people has long been a prime component of rural development strategies. Originally, these strategies focussed on concessional loans to farmers. More recently, however, this approach has been replaced by much wider financing for rural activities, with lower transaction costs. By creating rural financial markets and integrating them with general financial markets, it may be possible to mobilise substantial domestic savings as the main capital resource for rural people-and to reduce their dependence on concessional outside funds. Where urban-biased financial policies have inhibited the creation of effective rural financial institutions, new policies and strategies should seek to integrate rural and urban financial services and thus promote the greatest financial efficiency and lowest credit costs for rural people.

Involving rural people (particularly women) in decision-making

Above all, planning for rural energy development should have a decentralised component and should involve rural people-the customers-in planning and decision-making. And special attention should be devoted to involving women, because they bear the burden of traditional energy systems and are likely to be the greatest beneficiaries of improved systems. A major driving force for the move towards decentralisation has been the recognition of the limited extent to which benefits have flowed to rural people from the investments already made. More active involvement

of rural people (particularly women) and their institutions in identifying rural energy problems, and in formulating and implementing plans to overcome them, would result in more efficient, rational use of resources and more equitable sharing of the benefits of development.

Decentralisation of rural energy planning is wise for other reasons as well. Rural energy systems are based primarily on biomass, a local energy resource. Although historically this has involved direct combustion of biomass for cooking or heating (as this chapter has shown), clean, convenient, modern energy carriers can also be derived from biomass. Consequently, an assessment of the demand and supply flows and of desirable interventions must all also occur on the same geographic scale. Through their superior knowledge of the local situation, local people-women in particular-can be integral parts of the solution.

Strategies for expanding access to modern energy services

Often, policies ensuring that supplies-even from centralised production sources-are reliable and stable can promote the use of modern energy carriers. The Hyderabad, India, example (see above) shows that by the simple expedient of stabilising LPG supplies, the local government was able to encourage many households to shift from biomass to LPG for cooking.

Where integrated rural development has

> Where integrated rural development has been pursued, the availability of affordable modern energy supplies has proven to be a catalyst for economic and social transformation.

For rural electrification through grid extension, rural cooperatives seem to be a viable alternative to grid extension by the large parastatals that have dominated power generation in developing countries. In Bangladesh financial and technical failures of public power utilities in 1980 led to a government-supported take-over of its parastatals by rural electrification cooperatives. Now numbering 45, the cooperatives have engineered a rapid expansion of grid-based rural electricity supply that serves 1.6 million consumers-as many as the public sector in urban areas. Power outages have fallen dramatically, while revenue collection has improved from 91 to 98 percent, despite higher tariffs. Most important, the cooperatives have fostered an alternative structure to meet a demand that was previously unexpected in such a poor country. They have also demonstrated that consumers have considerable interest in getting access to electricity and are willing to pay for reliable service.

More effective electric grid extension measures can also help promote the wider availability of electricity from local biomass sources by making

village-scale biopower-generating technology more attractive to investors. Grid access would make it possible to operate biopower plants as baseload units, thereby increasing capacity utilisation and reducing generation costs per kilowatt-hour. Grid access would enable rural populations to sell into the grid electricity produced in excess of local needs-until local rural industrial capacity could be increased to more fully use the electricity produced this way (case 2 in the annex). Thus a promising new approach would be to couple grid extension in regions rich in crop residues (or other suitable biomass resources) to measures that encourage village-scale biopower generation.

This strategy would also make investments in grid extension more attractive. The availability of baseload biopower on these grids would enhance grid capacity utilisation and make transmission costs per kilowatt-hour much lower than when electrons instead flow from large central power plants to rural areas to serve small, scattered, peaky rural electrical loads.

Policies that make grid access possible are needed to facilitate the launch of such baseload biopower technologies on the market. Policies promoting increasing competition in electricity generation would be helpful. But consideration also has to be given to the fact that, when any new technology is introduced, its cost is higher than that of the established technology it would replace. That remains the case until enough new

plants have been built to buy down the cost of the new technology along its learning curve to prospective market-clearing price levels (chapter 12).

One way to pursue technology cost buy down in a competitive electricity market is to require that each electricity provider include in its portfolio a small but growing fraction provided by biopower or other renewable energy supplies. This requirement would be imposed during a transitional period as new renewable energy industries are being launched on the market. Power generators could either produce this renewable electricity themselves or purchase renewable energy credits that are sold in a credit trading market. Experiments with this mechanism are being conducted in the United States (where it is called a renewable portfolio standard) and in Europe (where it is called green certificate markets). The concept has great promise for developing countries.

A major challenge in extending energy services to rural areas is to find and pursue the least costly mix of energy options (centralised and decentralised, fossil and renewable, end-use efficiency improvements) for a particular region. This might be achieved, for example, through concessions for both cooking fuels and electricity. Concessions grant the exclusive right to provide energy services in exchange for the obligation to serve all customers in the region. They offer the advantage of being able to reduce transaction costs greatly in serving large numbers of small customers, relative to other mechanisms. Concessionaires ought to have

the flexibility to choose the least costly combinations of technologies in meeting their obligations. The rural energy concessions recently introduced in Argentina illustrate how the concept might work (box 10.5).

BOX 10.5. A CONCESSION SCHEME FOR RURAL ENERGY DEVELOPMENT IN ARGENTINA

Argentina recently began implementing an innovative rural energy plan to encourage private sector involvement in rural energy services. To begin with, the programme targets eight provinces with 1.4 million people and 6,000 facilities without access. In each province, private companies bid for the right to provide electricity to the people and to the schools, medical centres, drinking water facilities, and other public facilities without access. Solar photovoltaic panels, small wind turbines, micro hydropower, and diesel-driven generators compete on a least-cost basis.

Preliminary analyses show that in most cases renewable technologies will be competitive with diesel generators. A large share of household supply will be through solar photovoltaic home systems. Total investment for all provinces amounts to $314 million, with a 55 percent subsidy from provincial, federal, and World Bank funds to cover initial capital investments. The winning bids will be those seeking the lowest government subsidy per energy hook-up.

In 1996 two concessions were awarded in Jujuy and Salta provinces. In Jujuy, after solving some initial problems with the tariff structure proposed in the bidding papers, 500 of 2,000 new users are now served through renewable sources, and a programme to supply 550 additional users through solar home systems is in progress. By 1998 solar systems were installed in 220 schools in Salta province, which aims to achieve full coverage of public service electrification (including schools and first-aid medical centres) in 2000.

In April 1999 a $30 million loan from the World Bank and a $10 million subsidy from the Global Environment Facility were approved. These funds will help finance the national government's share of subsidies for the first eight provinces to adopt the programme, as well as overcome barriers to the use of renewable energies. Concessions to provide electric power to significant portions of the population within three years were granted in the next six provinces to adopt the programme in late 1999 and early 2000. Eventually, all rural Argentine provinces will participate in the programme.

Source: Covarrubias and Reiche, 2000.

Strategies for making modern energy services affordable

Although policies aimed at widening access to modern energy services are necessary, they are often insufficient to deliver modern energy services to all rural residents. Modern energy technologies are useful only to those who can afford to adopt them. Even the more affluent rural households

typically cannot afford to purchase photovoltaic systems, which may be the only plausible electrification option for scattered rural households. Moreover, the very poorest households are unable to pay for even less capital-intensive modern energy options. And such households are the majority in the poorest countries: 37 of the countries listed in the World Bank's *World Development Report 1998/99* had a 1997 GDP per capita below $500 (unadjusted for purchasing power parity).

Historically, energy price subsidies have been used extensively to promote wider use of modern energy carriers. But energy price subsidies are problematic. The welfare objective embodied in such subsidies is often not realised because of their diversion to unintended uses. Typically, there is a disproportionate exploitation of the subsidies by the more affluent, who could afford to pay unsubsidised prices. Such subsidies help explain the poor financial conditions of many parastatal energy companies, and have made continued expansion of energy supplies difficult (chapter 12). Energy price subsidies should be a policy of last resort to deliver modern energy services to rural areas.

When attempting to increase the level of energy services provided, a central question is: what is affordable? There is frequent mention of affordability, but there has been no rigorous quantification of this concept. One might argue that a consumer's current energy expenditures-for example, on kerosene for lighting-are a good indicator of what that

consumer is prepared to spend for electric lighting. In some cases, however, the consumer is prepared to spend more for a new technology if it is safer or more convenient.

Policy reforms to make capital resources more readily available for small-scale rural energy investments would be especially helpful in making modern energy affordable to small rural consumers. Various microfinance schemes are being tried (box 10.6), and some are proving quite successful. When the poor have access to microfinance, they are no longer beneficiaries of government and donor largesse but clients with assets, whose preferences and needs must be respected. Microfinance has demonstrated success not only in providing access to energy services for poor households, but also in generating income and alternative economic activities. Microfinance is facilitating access to affordable modern energy technologies for which many people are willing to pay the full cost.

Poor Indian households that currently buy kerosene for lighting could afford electric lighting if energy-efficient fluorescent bulbs were used (Reddy, 1999). An appropriate microfinance scheme could make investment in fluorescent lights a viable option, even for poor households, if total spending on electricity plus debt servicing was less than maximum household spending on energy (about 15 percent). The combination of modern technology and microfinance can thus widen the window of opportunity. Because of the capital-intensive nature of photovoltaic and

other renewable energy technologies, microfinance schemes are especially important to promote their widespread dissemination (box 10.7).

BOX 10.6. ALTERNATIVE APPROACHES FOR FINANCING SMALL-SCALE RURAL ENERGY TECHNOLOGIES

At the smallest scales, many sustainable energy technologies (including small-scale wind and hydropower supplies and photovoltaics for homes) cost a few hundred dollars. Buying them outright is impossible for most rural households in developing countries. But an important minority of households, communities, and small businesses can afford to buy them with credit. The main obstacle to serving this crucial market is the reluctance of banks to manage numerous small loans and to lend without collateral or other guarantees against loan defaults. A variety of innovative approaches are being used to overcome this obstacle:

- **Financing through dealers.** Banks transfer the collateral problem from the end user to dealers by lending to dealers, who in turn lend to purchasers using payment schemes compatible with their income. Dealers must bear the financial risk along with technical risks. This system is best suited to large, relatively high-income rural markets.

- **Financing through energy service companies.** These companies can replace dealers as the financing intermediary. Companies typically require greater efforts to establish higher funding levels, because they provide a more comprehensive installation and back-up service to clients.

- **Revolving funds (with grant support).** A bank takes on the risk of operating a revolving loan fund, usually with start-up capital provided by a grant.

- **Loan aggregation through cooperatives.** To avoid the high costs of servicing many small loans, prospective borrowers form a community association (or enlarge the functions of an existing village or farmer cooperative). Banks lend to the cooperative or lease the energy systems but retain ownership of the equipment in case of payment defaults.

- **Concessional funding for public sector objectives.** The government contracts and pays a local company to provide energy services that meet development objectives, such as photovoltaic lighting for schools. This provides entry capital for the company to offer credit and expand its business to other local markets, such as photovoltaics for households, health clinics, and community centres.

- **Payment for energy services.** Payment for outputs, such as irrigation and drinking water, have been used to fund the recurrent operation and maintenance costs of small-scale energy systems. These cost streams are usually hard to fund, or remain unfunded, when loans target the capital cost.

Most of these approaches demand high levels of local participation and so take time to mature. Participation must start at the concept development stage, so that local people can decide which schemes and parameters are most appropriate.

Source: EC and UNDP, 1999.

Microfinance by itself is no panacea, however. Two other factors limit the affordability of energy services: the high costs of imported energy products (including high inherent costs and inefficient procurement of small quantities) and the low incomes of the very poorest households. But international industrial joint ventures that manufacture modern energy technology with gradually increasing domestic content can, over time, reduce costs relative to the cost of the same technology if imported (Weise and others, 1995; see also the case study of wind-diesel hybrid technology in China in chapter 7). Such cost reductions lead to expanded market opportunities, which lead to further cost reductions resulting from higher production volumes. The keys to success in creating this kind of virtuous cycle of cost reduction and market expansion are policies that facilitate the formation of such joint ventures and steer them towards the provision of energy services for rural areas (chapter 12).

BOX 10.7. THE GRAMEEN SHAKTI PHOTOVOLTAIC PROGRAMME IN BANGLADESH

In 1996 the Grameen Bank of Bangladesh, a microlending agency with more than 1,000 branches and 2 million members, initiated a programme of loans for photovoltaic home systems to serve those without access to electricity. The loans are administered by a nonprofit rural energy company, Grameen Shakti, and call for a small down payment.

Grameen Shakti's first initiative has been a 1,000-unit project to understand better a number of important issues concerning household photovoltaic systems. These include:

- Technical performance of these systems in rural Bangladesh.
- Acceptance of the systems by the poor.
- Income-generating potential of light in the evening.
- Affordability, factoring in technical improvements and economies of scale.
- The training, monitoring, and evaluation expertise that would be required to replicate this project if it proves successful.

Grameen Shakti expects that 100,000 photovoltaic systems will be operating in rural Bangladeshi homes in 2000. The bank plans to expand this service by offering small loans for wind power and biogas plants. Demonstration projects are under way to determine the most appropriate financing packages for these technologies.

The very poorest households may need higher incomes as well as microfinance to afford modern energy supplies and end-use devices. Increasing the incomes of the rural poor through macroeconomic policies is an especially daunting challenge and takes a long time. But energy policies that facilitate the introduction of low-cost electricity generation for rural industrialisation could effectively promote income generation.

Especially promising are the possibilities for electricity generation from low-cost crop residues in agriculture-intensive regions. Moreover, village-scale, crop-residue-based biopower technologies offer the possibility of near-term income from gathering biomass and delivering it to conversion facilities. This could help the poor pay for modern energy supplies without having to wait for rural industrialisation opportunities to materialise (case 2 in the annex). A key to making such income-generating activities viable seems to be the opportunity to sell into the grid electricity produced in excess of local needs (see the section above on small-scale biopower).

Pursuing all the above strategies might still leave the very poorest households in some areas unable to afford convenient energy services. If so, subsidies may still be needed. As noted, to stimulate the use of new technologies (such as fluorescent light bulbs), one-time equipment

subsidies are preferable to continued price subsidies.

To sum up, sustainable development implies that modern energy carriers need to be made affordable to satisfy the basic needs of all rural residents. Policies are needed that will make pursuing this objective profitable. If a subsidy is needed, it might be provided as an integral part of a new social contract that creates highly competitive conditions in the energy sector (a key element of ongoing energy reforms), complemented by the establishment of a public benefits fund financed with wire and pipe charges imposed on electricity, oil, and gas providers to protect the public interest under new competitive market conditions (see chapter 12 for a discussion of public benefits funds). Specifically, some fund revenues could subsidise the basic energy needs.

This public benefits fund strategy could be made entirely consistent with a shift to greater reliance on market forces to more efficiently allocate resources. If, for example, an energy concession proved to be the preferred way to deliver modern energy services to a particular rural area, and if the concession was awarded competitively, market forces would be brought into play to find the least costly mix of energy technologies with the least amount of subsidy to satisfy the concessionaire's obligation to provide modern energy services to all.

Conclusion

Between 1970 and 1990 rural electrification from grids brought electricity to 800 million additional people. In addition, in the past 20-30 years a number of innovative schemes have been developed to commercialise improved cooking stove, biogas, and producer gas systems; photovoltaics; wind; and so on-with the result that several hundred million people have improved their access to energy. Perhaps as many as 600 million people have benefited from these innovations. Yet despite these efforts to improve energy services to rural areas, the population without access to such services has stayed about the same: 2 billion.

The task is daunting but not hopeless. Technologies can be deployed immediately or in the near term to improve energy services for rural areas. These technologies will lead to dramatic advances in the quality of life for rural populations. These advances can be achieved at costs that are within the means of governments and beneficiaries. They also require quite modest increases in the magnitudes of total energy supplied to the countries involved. They offer attractive options for decision-makers seeking quick political pay-offs before the next popular judgement of their performance. Even more exciting is the possibility of interesting new technologies that might be developed and exploited. All such possibilities would enable rural populations to climb up the energy ladder, leapfrog to higher rungs on the ladder, or even reach new rungs that could be added near the top of the ladder.

Through their superior knowledge of the local situation, local people - women in particular - can be integral parts of the solution.

New policies are needed to bring the top of the energy ladder within reach of all rural people. Past efforts to deliver modern energy to rural areas have often been ineffective and inefficient. Some recent programmes are showing good results, but more promising new approaches need to be tested to determine if they can address poverty, equity, environmental, and public health concerns in the context of the ongoing global restructuring of energy industries. Much can be done towards these ends without resorting to large subsidies if competitive market conditions are fostered and complemented by measures to protect the public interest. Subsidies should be reserved for situations in which new strategies alone cannot make modern energy widely available. Even then, fuel price subsidies should be avoided if basic needs can be addressed by alternatives, such as subsidised purchases of energy-efficient equipment. Sound policies to accelerate the wide availability of modern energy services in rural areas could lead to even more dramatic improvements in the rural quality of life without creating large demands on public treasuries.

Annex. Case studies of crop-residue-derived modern energy carriers in

China

In densely populated countries that are largely self-sufficient in food production and are prolific generators of crop residues, thermochemical gasification of crop residues can provide an attractive means of providing both clean cooking fuel and electricity or combined heat and power (CHP) to satisfy basic human needs and generate additional electricity in support of income generation and rural industrialisation. Prospects in this regard are here illustrated by three case studies for China that illustrate the prospects for providing:

- **With existing technology, residue-derived producer gas as a clean cooking fuel at the village scale.**

- **With medium-term (5-10 year) technology, cooking gas plus CHP at the village scale, with residue-derived producer gas.**

- **With long-term (10-20 year) technology, both electricity suitable for rural industrialisation and a synthetic fluid fuel for cooking (synthetic LPG or DME derived from synthesis gas; see chapter 8) that is safe as well as clean.**

There are three reasons to focus on China in studying this approach to making modern energy carriers widely available in rural areas. First, China satisfies the criteria of being densely populated, self-sufficient in food, and

a prolific generator of crop residues. About 376 million tonnes a year (about half the total residue generation rate) are potentially available for energy; the rest is used for paper-making, forage, or returned to the fields to sustain soil quality (Li, Bai, and Overend, 1998). The energy content of these residues is equivalent to 15 percent of the coal energy use in China in 1998.

Second, China has a severe new air pollution problem caused by the burning of crop residues in the field at harvest time, a consequence of the rising affluence of farmers. Traditionally, in poor agricultural communities of China, residues were fully utilised for heating, cooking, and other purposes. But as incomes have risen, growing numbers of farmers have become less willing to gather residues from the fields and store them for use throughout the year-preferring instead to buy coal briquettes or LPG as needed. As a result, excess crop residues that do not readily decay (because they dry out too quickly)for incorporation into the soils have been burned off in the fields to avoid insect infestation problems. The resulting air pollution has been severe-often even closing airports near harvest time. As a response, the government in 1999 banned burning crop residues near airports, railroads, and highways. The ban will be difficult to enforce, however, unless alternative productive uses of residues can be found.

Third, a key to providing low-cost electricity from crop residues as a

coproduct of cooking gas is being able to produce baseload electricity and to sell electricity produced in excess of local needs into the electric grid. In most developing countries, this is not yet feasible because few rural communities are hooked up to grids. But in China, 87 percent of rural households are connected, in comparison with an average of about 33 percent for all other developing countries. Thus China stands out as a strong candidate country for launching small-scale biopower technologies in the market.

Case 1. Cooking with producer gas generated at the village scale

With technology currently available in China, it is feasible to provide clean cooking gas derived from crop residues at the village scale through partial oxidation in air, as illustrated by recent experience in Shangdong Province.[10] In May 1996 a village-scale crop residue gasification system serving village households with producer gas for cooking went into operation in Tengzhai village (216 households, 800 people), Huantai County, Shangdong Province (the second village-scale gasification system installed in the province), using an atmospheric pressure, air-blown, downdraft gasifier developed by the Energy Research Institute of the Shangdong Academy of Sciences. Researchers at the institute also carried out detailed socio-economic studies of the implications of the technology and of costs in relation to benefits.

The gasifier requires 0.25 tonnes of crop residue per capita to meet the annual cooking needs of villagers. About 12 percent of the residues generated by the village's wheat and corn crops are adequate to meet all its cooking energy requirements. Researchers estimated that, with the producer gas cooking system, cooking time for housewives is reduced from 3.0 to 1.5 hours a day.

In a survey of 30 randomly selected households, the researchers found that this technology was regarded as being as good as or better than coal or LPG (the major technologies displaced) with regard to price, convenience, reliability of supply, environmental impact, and working intensity of housewives (all the issues investigated in the survey) by 97.5 percent or more of all households surveyed for each issue.

The total capital cost for the entire project (with an expected 10-year project life) was 378,000 yuan ($47,000, or $220 a household), a third of which was provided by a government subsidy. The producer gas is sold to villagers at a price that is a third of the market price for LPG on an equivalent-cooking-service-provided basis.[11] At this selling price, the project is not cost-effective, even with the capital subsidy. However, if the gas selling price were raised to two-thirds of the equivalent market price for LPG, the technology would be cost-effective without any capital subsidy, generating an internal rate of return of 17 percent. At this higher gas price, the annual cost of cooking fuel per household would be 360 yuan

($45) a year, about 25 percent less than the fuel cost for cooking with coal.

Case 2. Combined heat and power systems using producer gas generated at the village scale

Although desirable as a way to make an affordable, clean, convenient cooking fuel available to villagers, the strategy described above will not solve the air pollution problem caused by burning excess residues. However, using residues in excess of what are needed to make cooking gas power generation or CHP could solve the problem.

This case discusses the prospects for improving village living conditions through the 'trigeneration' of cooking gas, hot water for space heating, and electricity from a village-scale gasifier that converts crop residues (corn stalks) into producer gas (Henderick and Williams, 2000). The system is designed to satisfy all cooking needs in the village with a clean gas, plus meet all village electricity needs, plus generate much more electricity for sale into the grid, plus generate hot water through waste heat recovery at the biopower plant for distribution to village households through a district heating system that would satisfy all space-heating needs (especially important in Jilin Province, where winters are very cold). For specificity, the analysis is for a hypothetical 100-household village (400 residents) in Jilin Province, where about half the residue generated

could potentially be exploited for energy purposes at a rate of about 6.5 tonnes a household per year (Cao and others, 1998).

With currently available biopower technology, electricity could be produced at the least cost with diesel-engine generator sets operated in dual-fuel mode, using producer gas as the primary fuel, plus pilot diesel fuel for ignition purposes (see the section in the main text of the chapter on small-scale biopower using producer gas). Because this technology is more capital-intensive than conventional diesel technology (table A10.1), a high level of capital utilisation (high capacity factor) is often required to reach economically attractive generation costs. Local electricity demand in poor rural areas is often inadequate to make the required high capacity factors feasible. If electricity could be sold into the electric grid, high capacity factors could often be realised.

A microturbine providing 75 kilowatts of electricity, a second-generation small-scale biopower technology (see the section on small-scale biopower using producer gas), was selected for the detailed design of a village trigeneration system. The microturbine is a technology for which the potential generating cost using low-cost residues is low enough (see table A10.1) to make the technology quite attractive for selling electricity into the grid. The energy balance for the village trigeneration system based on the use of this micro-turbine is shown in figure A10.1.

The estimated initial investment (base case) for the system is $1,800 a household, a third of which is for gas and for infrastructure to pipe hot water. It is assumed that the infrastructure investment is covered by a loan from the government at 6 percent interest, and that the rest of the investment is covered by equity capital provided either by an independent power producer or by a villager-owned corporation. (Village corporation financing is plausible because the required capital is equivalent to less than three years of the average savings rate-38 percent of income in 1998-for Jilin's rural population.) For the village corporation option, the average net cash flow to villagers (income from crop residue sales plus revenues to the corporation minus expenses of the corporation) is adequate to cover all expenditures on energy by the villagers for the 20-year life of the system.[12]

TABLE A10.1 COSTS OF ELECTRICITY WITH ALTERNATIVE ENGINE-GENERATORS FUELLED WITH DIESEL OIL AND/OR PRODUCER GAS DERIVED FROM CROP RESIDUES

System type[a]	Diesel engine		Spark-ignition engine	Microturbine
	Diesel only	Dual-fuel[b]		

Engine-generator set				
Equipment lifetime (years)[c]	6	6	6	10
Rated power output (kilowatts)	80	100	160	80
De-rated power output (kilowatts)[d]	80	80	80	80
Thermal efficiency, lower heating value (percent)[e]	34	27	21	28
Installed equipment cost (dollars per rated kilowatt)[f]	181	181	362	350
Installed equipment cost (dollars per de-rated kilowatt)	181	226	724	350
Present value of lifecycle capital investment for the engine-generator set (dollars per de-rated kilowatt)[g]	330	413	1,320	463
Total system (including building plus gasifier plus gas clean-up)[h]				
Initial cost (dollars per de-rated kilowatt)[i]	243	680	1,280	850
Present value of lifecycle capital investment for the total system (dollars per de-rated kilowatt)[j]	392	960	1,970	1,070
Operating costs				

Diesel fuel (dollars per hour, at full power output)[k]	5.48	1.65	0	0
Crop residues (dollars per hour, at full power output)[l]	0	0.39	0.66	0.50
Lubricating oil (dollars per hour, at full power output)[m]	0.21	0.42	0.42	0
Labour (dollars per hour during operation, at full power output)[n]	0.12	0.23	0.23	0.23
System maintenance (dollars per year)[o]	1,500	2,800	2,800	3,300
Levelised life-cycle electricity generation cost (cents per kilowatt-hour)				
Total capital cost	0.92	2.26	4.63	2.51
Diesel fuel	6.85	2.06	0	0
Biomass	0	0.49	0.83	0.62
Lubricating oil	0.26	0.53	0.53	0
Maintenance	0.34	0.62	0.62	0.73
Labour	0.16	0.33	0.33	0.33
Total (cents per kilowatt-hour)	**8.5**	**6.3**	**6.9**	**4.2**

a. All costs are in 1998 U.S. dollars. All systems are designed for an electrical output capacity of 80 kilowatts of electricity, and operation at 65 percent average capacity factor, so that annual electricity generation is 456,000 kilowatt-hours. Costs are calculated for a 12 percent real discount rate and a system lifetime of 20 years, so that the capital recovery factor is 0.134. b. Dual fuel refers to operation on producer gas plus pilot oil. It is assumed that producer gas displaces 70 percent of the diesel fuel required for standard operation on diesel fuel only. c. It is assumed that reciprocating internal combustion engines have 6-year (34,000-hour) lifetimes. The 10-year (57,000-hour) lifetime for the microturbine is an estimate by Honeywell. d. Relative to operation on diesel fuel, a diesel engine operated on producer gas plus pilot oil is typically de-rated 20 percent. For spark-ignited engines operated on producer gas, a 50 percent de-rating relative to operation on gasoline is typical. There is no de-rating penalty for microturbines operated on producer gas (Henderick, 2000). e. The assumed efficiencies (producer gas to electricity) for internal combustion engines converted to run on producer gas (21 percent for spark-ignition engines and 27 percent for diesel engines) are representative (Reed and Das, 1988). For the microturbine, 28 percent is representative of Honeywell's 75-kilowatt model (their target is 30 percent). The overall conversion efficiency (crop residue to electricity) is obtained by multiplying these efficiencies

by the 70 percent gasifier efficiency. f. The diesel engine capital cost is from Mukunda and others (1993). The spark-ignition engine is assumed to be an industrial gas engine, for which the capital cost is typically twice that of a diesel (McKeon, 1998). Honeywell product literature (1998) estimates year 2003 installed equipment cost at $350-450 a kilowatt for its 75-kilowatt microturbine. g. Present value of the life-cycle capital investment includes the installed equipment cost plus future replacements during the 20-year life cycle, less equipment salvage value at 20 years. h. On the basis of Mukunda and others (1993), capital costs for gasification and gas clean-up are assumed to be $1,160 for the gasifier, $8,700 for the cooling and cleaning system, $11,600 for a control system, and $5,800 for a building ($1,740 if diesel only). For the microturbine, an additional fine filtration cleaning unit costing $20 a kilowatt is assumed. i. The total initial cost includes a 20 percent increment over the installed equipment cost to allow for engineering and contingencies. j. During the 20-year life cycle, the gasifier is replaced three times (6-year life), and the clean-up and control systems are replaced once (10-year life), while the building requires no replacement (Mukunda and others, 1993). k. The cost of diesel fuel is assumed to be $0.25 a litre. l. For rural Jilin Province, China, the cost of gathering corn stalks from the field and delivering them to the trigeneration facility modelled in Henderick and Williams (2000) is estimated to be 45 yuan a tonne ($0.33 a

gigajoule), on the basis of data for the province provided by Cao and others (1998). m. On the basis of Mukunda and others (1993), lubricating oil requirements are assumed to be 1.36 grams a kilowatt-hour for dual-fuel engines; for spark-ignition engines the same value is assumed, and half this rate is assumed for conventional diesel engines; microturbines require no lubricating oil. Also on the basis of Mukunda and others (1993), the lubricating oil cost is assumed to be $3.50 a litre ($3.87 a kilogram). n. On the basis of Mukunda and others (1993) for rural India, during the 65 percent of the time the engine is assumed to be operating at full output, labour costs are $0.23 an hour (4 rupees an hour) for two workers for dual-fuel systems-assumed to be the same for spark-ignition engines and microturbines. Labour costs at half this rate are assumed for conventional diesel engines. In addition, it is assumed that these labour cost rates are applicable for 14 hours a week during downtime, for maintenance, preparation, and so on. o. On the basis of Mukunda and others (1993), annual maintenance costs are estimated as fixed percentages of installed building and equipment costs (not including engineering and contingencies) for the diesel, dual-fuel, and microturbine cases. The assumed percentage for diesel and dual-fuel engines is 10 percent; that for microturbines is assumed to be 8 percent. The assumed percentage for the building, gasifier, and gas clean-up is 5 percent; for the control system, 2 percent. It is assumed that the maintenance costs

for the spark-ignited engine case are the same as for the dual-fuel engine case.

Source: Based on Henderick and Williams, 2000.

The low-interest government loan for piping infrastructure might be justified as a cost-effective measure for avoiding the health costs of indoor air pollution associated with burning solid fuels for cooking and heating. For the hypothetical village, the annual health damage costs avoided would be $4,800 (assuming the average per capita value for all rural China; World Bank, 1997), more than three times the cost savings to the villagers, as a result of having debt instead of equity financing for piping.

Poor households that own no crop residues might earn income to cover energy expenditures by being paid by rich farmers to remove crop residues from their fields (for example, to enable them to comply with the ban on field burning of residues); residue recovery from the farmland of less than five average households would enable a poor household to earn enough income to cover all energy expenditures.

Case 3. Coproduction at industrial-scale of synthetic liquid petroleum gas and electricity from crop residues

The trigeneration technology described above could be improved if the cooking fuel provided were safe as well as clean (for example, producer

gas contains carbon monoxide, so the risk of leaks poses a danger). This might be realised through the coproduction, at industrial scales, of electricity and synthetic liquid petroleum gas (SLPG) or dimethyl ether (DME)-synthetic fuels well suited for cooking, the use of which would involve no risk of carbon monoxide poisoning.

A preliminary design of a plant that would convert grain crop residues into SLPG and electricity using a once-through Fischer-Tropsch liquids plant coupled to a biomass integrated gasifier combined cycle (IGCC) plant has been carried out (Larson and Jin, 1999) at plant scales appropriate for Jilin Province, the corn belt of China, which produced 15 million tonnes of corn in 1995 (13 percent of the country's total). The technology would build on advances that are being made for liquid-phase syngas reactors that are being developed for the coproduction of synthetic liquid fuels and electricity from fossil fuel feedstocks (chapter 8).

The design involves 10-megawatt-electric biomass IGCC plants producing SLPG as a coproduct (250 barrels of crude oil equivalent a day). For the corn crop residue densities characteristic of Jilin, residues would have to be gathered from cornfields within a 11-kilometre radius to meet feedstock needs at the plant. Such plants could convert 15 percent of the biomass feedstock to electricity and 28 percent to LPG. Preliminary estimates are that the SLPG produced this way in rural Jilin might be competitive with conventional LPG, once biomass IGCC technology is established in the

market (Larson and Jin, 1999). As discussed in chapter 7, biomass IGCC technology has advanced to the point where it is now being demonstrated in various parts of the world, building on the experience that has already brought coal IGCC technology to commercial readiness (chapter 8).[13]

If the technology could be used with all the 376 million tonnes of crop residues per year potentially available for energy purposes in China, it could provide 1.4 exajoules a year of SLPG along with 210 terawatt-hours a year of electricity. This much LPG could meet-in the form of a super-clean fuel-the cooking needs of 560 million people (about 70 percent of the rural population projected for 2010), while generating electricity at a rate equivalent to the output of 2.5 Three Gorges power plants (the Three Gorges plant's output is 18 gigawatts of electricity). And whereas the electricity from the Three Gorges plant would have to be transmitted long distances to most customers, this residue-generated electricity would be produced in 3,400 power plants (each with output of 10 megawatts of electricity), which would typically be located close to the consumers they serve.

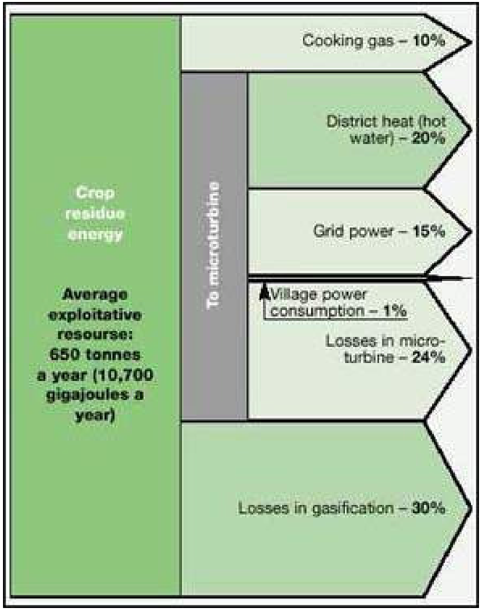

FIGURE A10.1. ENERGY BALANCE FOR A TRIGENERATION SYSTEM BASED ON THE USE OF PRODUCER GAS DERIVED FROM CROP RESIDUES IN A HYPOTHETICAL 100-HOUSEHOLD VILLAGE, JILIN PROVINCE, CHINA

Source: Henderick and Williams, 2000.

As in the case of the village-scale trigeneration system described above, with this technology the very poorest households could pay enough for electricity and clean cooking fuel to satisfy their basic needs by gathering

residues from the fields of rich farmers and delivering the residues to the energy conversion plants, thereby monetising their labour.

DME, which is expected to be easier to manufacture as a synthetic fuel than SLPG, would have similar properties as a cooking fuel. Although the technology for making DME is not as far advanced as that for SLPG, either option could probably be commercially ready by 2010-15 with a concerted development effort. The Institute of Coal Chemistry at the Chinese Academy of Sciences is investigating prospects for making DME from coal for cooking fuel applications (Niu, 2000).

Notes

1. The amount of time varies widely depending on the availability of biomass. Surveys have shown that in some regions, women spend close to an hour a day collecting firewood, and could spend more than two hours a day in areas where fuels are scarce (World Bank, 1996).

2. As discussed in the next section, many of the technologies associated with the intermediate rungs on the ladder pose greater development challenges than technologies associated with the top rungs.

3. For a family of five, 0.08 kilowatts per capita consumption for cooking is equivalent to 21 kilograms of LPG per month. Assuming that 30 percent of the 0.02 kilowatts per capita of electricity is consumed to support

community activities, the remaining electricity would be adequate to support six compact fluorescent light bulbs used for four hours a day in addition to a television for two hours a day plus a refrigerator-freezer with the average energy efficiency projected for new U.S. units in 2001.

4. For example, in China the energy content of crop residues is twice that of animal excrement on large and medium-size farms, and the fraction of crop residues recoverable for energy purposes (about half the total generation rate) is equivalent in terms of contained energy to about 20 percent of China's coal consumption rate (Li and others, 1998; Su and others, 1998).

5. Gasifiers are about 70 percent efficient in converting biomass energy into gas energy, and producer gas stoves are about 50 percent efficient. Thus the overall efficiency of converting biomass into heat energy used in cooking is about 35 percent, which is double or more the efficiency of typical biomass stoves.

6. In China the number without access to electricity in 1996 was only 110 million, less than 13 percent of China's rural population (Dai, Liu, and Lu, 1998).

7. Lubricating oil can contribute as much to the generation cost as natural gas fuel contributes to the generation costs of a modern large combined-

cycle power plant-compare tables 10.3 and 8.4.

8. If spark-ignited instead of compression-ignited engines were used for power generation, the need for diesel fuel could be eliminated entirely. But such engines are less efficient and more capital intensive than diesel engines, and they must be de-rated more (about 50 percent relative to operation on gasoline) than compression-ignition engines. As a result or are often not competitive (Henderick and Williams, 2000).

9. This is about half the total residue generation rate. The rest is used for paper-making, forage, or returned to the fields to sustain soil quality (Li, Bai, and Overend, 1998).

10. This case is based on Dai and Lu (1998), Dai and Sun (1998), and Dai, Liu, and Lu (1998).

11. The market price for LPG in the village is 3.3 yuan per kilogram ($8.30 per gigajoule).

12. It is assumed that villagers are paid $0.33 a gigajoule for residues delivered to the conversion facility. It is also assumed that gas is sold for $6 a gigajoule (somewhat less than the LPG price) and hot water is sold for $5 a gigajoule (lower than the gas price to discourage gas burning for heat), and that electricity is sold to villagers for $0.10 a kilowatt-hour (the price they would otherwise pay for grid electricity) and to the grid for

$0.05 a kilowatt-hour.

13. Demonstration projects include a Global Environment Facility-sponsored, 30-megawatt-electric IGCC project in northeast Brazil (chapter 7).

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