part III

are sustainable futures possible?

energy scenarios

CHAPTER 9

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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. ■

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

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; Nakićenović, Grübler, and McDonald, 1998; Nakićenović, 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.

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 (Nakićenović 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

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

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]

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 (Häfele, 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 (Nakićenović 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* (Nakićenović, Grübler, 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 (Nakićenović, Grübler, 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

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 2050 2100	5.3 10.1 11.7	5.3 10.1 11.7	5.3 10.1 11.7
Gross world product (trillions of 1990 dollars)	1990 2050 2100	20 100 300	20 75 200	20 75 220
Gross world product (annual percentage change)	1990–2050 1990–2100	**High** 2.7 2.5	**Medium** 2.2 2.1	**Medium** 2.2 2.2
Primary energy intensity (megajoules per 1990 dollar of gross world product)	1990 2050 2100	19.0 10.4 6.1	19.0 11.2 7.3	19.0 8.0 4.0
Primary energy intensity improvement rate (annual percentage change)	1990–2050 1990–2100	**Medium** –0.9 –1.0	**Low** –0.8 –0.8	**High** –1.4 –1.4
Primary energy consumption (exajoules)	1990 2050 2100	379 1,041 1,859	379 837 1,464	379 601 880
Cumulative primary energy consumption, 1990–2100 (thousands of exajoules)	Coal Oil Natural gas Nuclear energy Hydropower Biomass Solar energy Other Global total	8.9 – 30.7 27.6 – 15.7 18.4 – 28.7 6.2 – 11.2 3.7 – 4.2 7.4 – 14.3 1.8 – 7.7 3.0 – 4.7 94.0 – 94.9	17.5 15.3 15.8 10.5 3.6 8.3 1.9 4.3 77.2	7.1 – 7.2 10.9 12.2 – 12.9 2.1 – 6.2 3.6 – 4.0 9.1 – 10.1 6.3 – 7.4 1.4 – 2.2 56.9
Energy technology cost reductions (through learning)	Fossil Non-fossil	**High** **High**	**Medium** **Medium**	**Low** **High**
Energy technology diffusion rates	Fossil Non-fossil	**High** **High**	**Medium** **Medium**	**Medium** **High**
Environmental taxes (excluding carbon dioxide taxes)		**No**	**No**	**Yes**
Sulphur dioxide emissions (millions of tonnes of sulphur)	1990 2050 2100	58.6 44.8 – 64.2 9.3 – 55.4	58.6 54.9 58.3	58.6 22.1 7.1
Carbon dioxide emission constraints and taxes		**No**	**No**	**Yes**
Net carbon dioxide emissions (gigatonnes of carbon)	1990 2050 2100	6 9 – 15 6 – 20	6 10 11	6 5 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 2050 2100	358 460 – 510 530 – 730	358 470 590	358 430 430
Carbon intensity (grams of carbon per 1990 dollar of gross world product)	1990 2050 2100	280 90 – 140 20 – 60	280 130 60	280 70 10
Investments in energy supply sector (trillions of 1990 dollars)	1990–2020 2020–50 2050–2100	15.7 24.7 93.7	12.4 22.3 82.3	9.4 14.1 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: Nakićenović, Grübler, and McDonald, 1998.

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.

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.

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.

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).

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

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.

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.

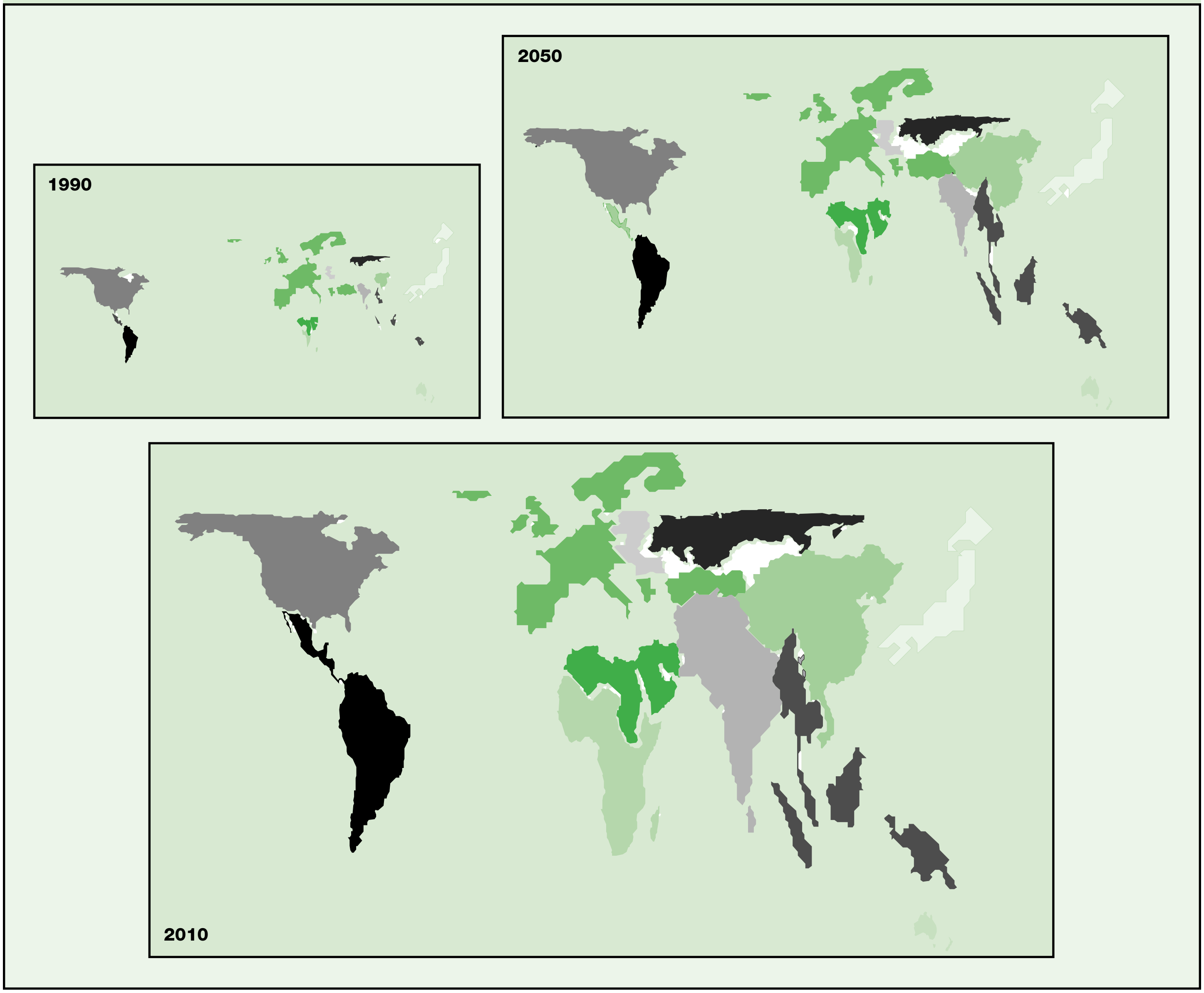
In figure 9.1, between 1990 and 2100 the world economy increases in size 10 times, from $20 trillion to $200 trillion (1990 dollars; or $24 trillion to $240 trillion in 1998 dollars). This leads to more equitable distribution of economic activities geographically, but the gap in per capita income remains 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.

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), Grübler (1994), Manne and Richels (1994), and Alcamo and others (1995). For instance, in the scenarios reviewed in Alcamo and others (1995), and Grübler (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 (Nakićenović, 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

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



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

Source: Nakićenović, Grübler, and McDonald, 1998.

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.

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

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: Nakićenović, Grubler, and McDonald,1998.

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.

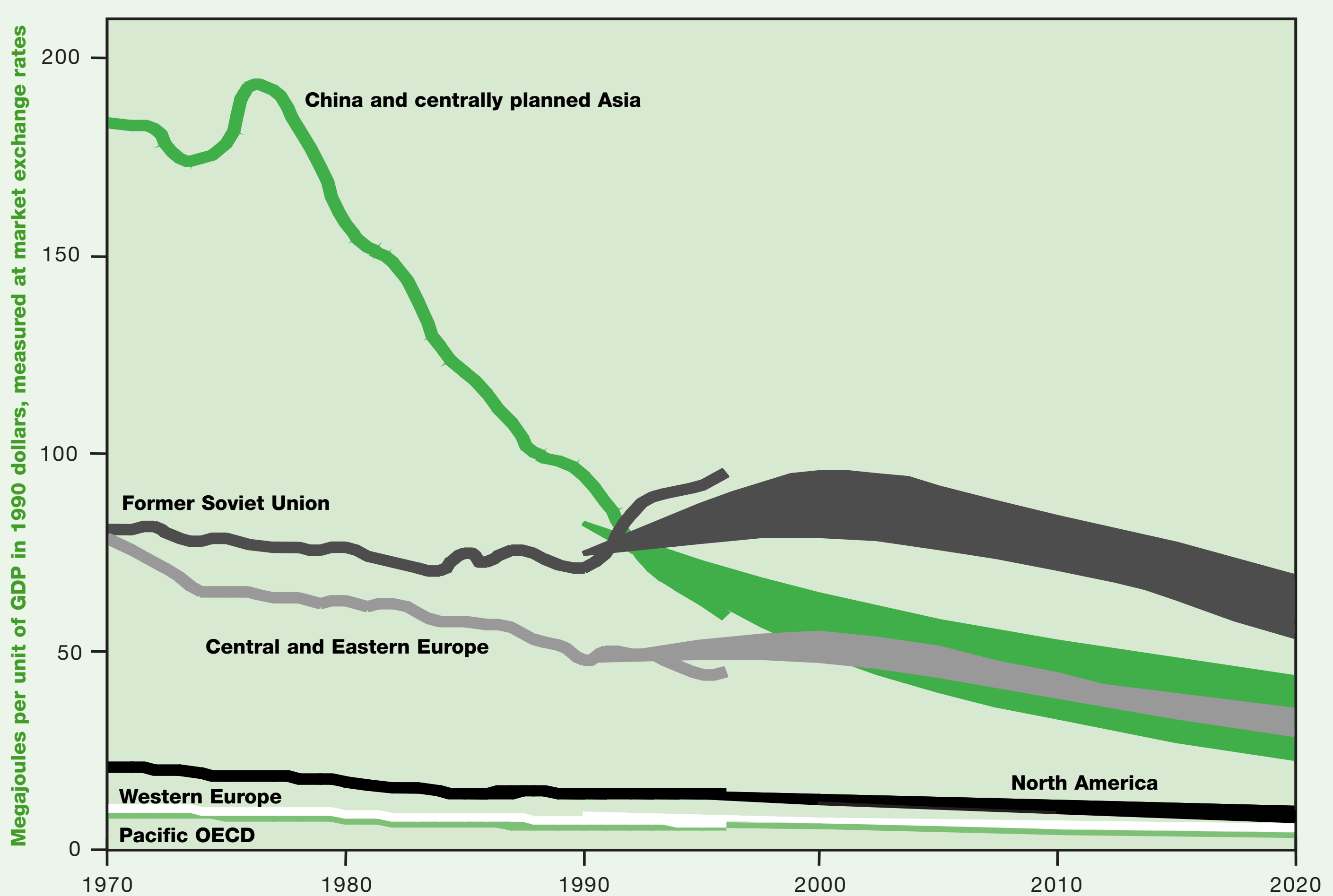
Primary energy requirements and supply

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.

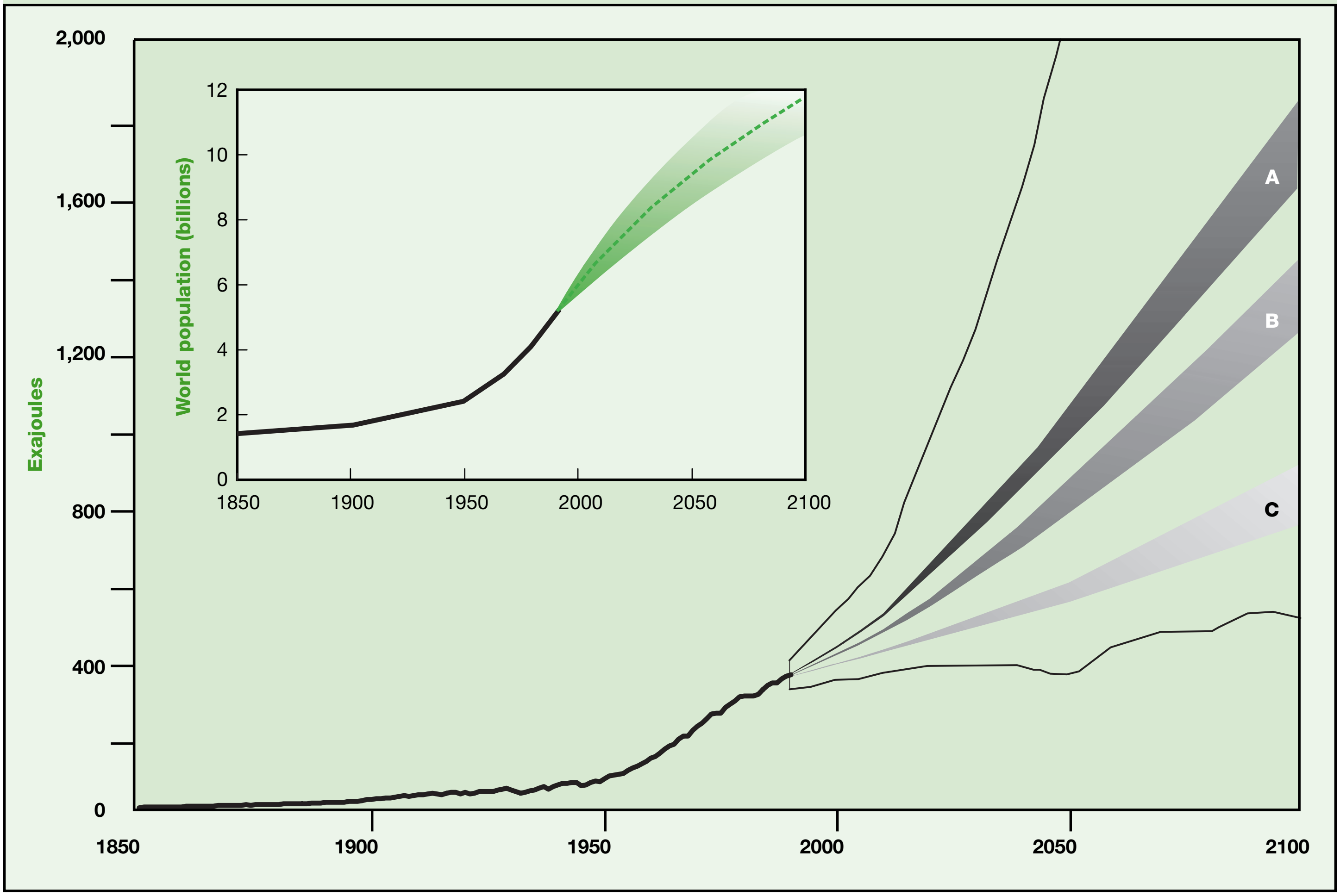
For comparison, figure 9.3 also shows the highest and lowest energy demand trajectories from the literature (Morita and Lee, 1998). The range of future energy requirements across the scenarios is

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: Nakićenović, Grübler, and McDonald, 1998.

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



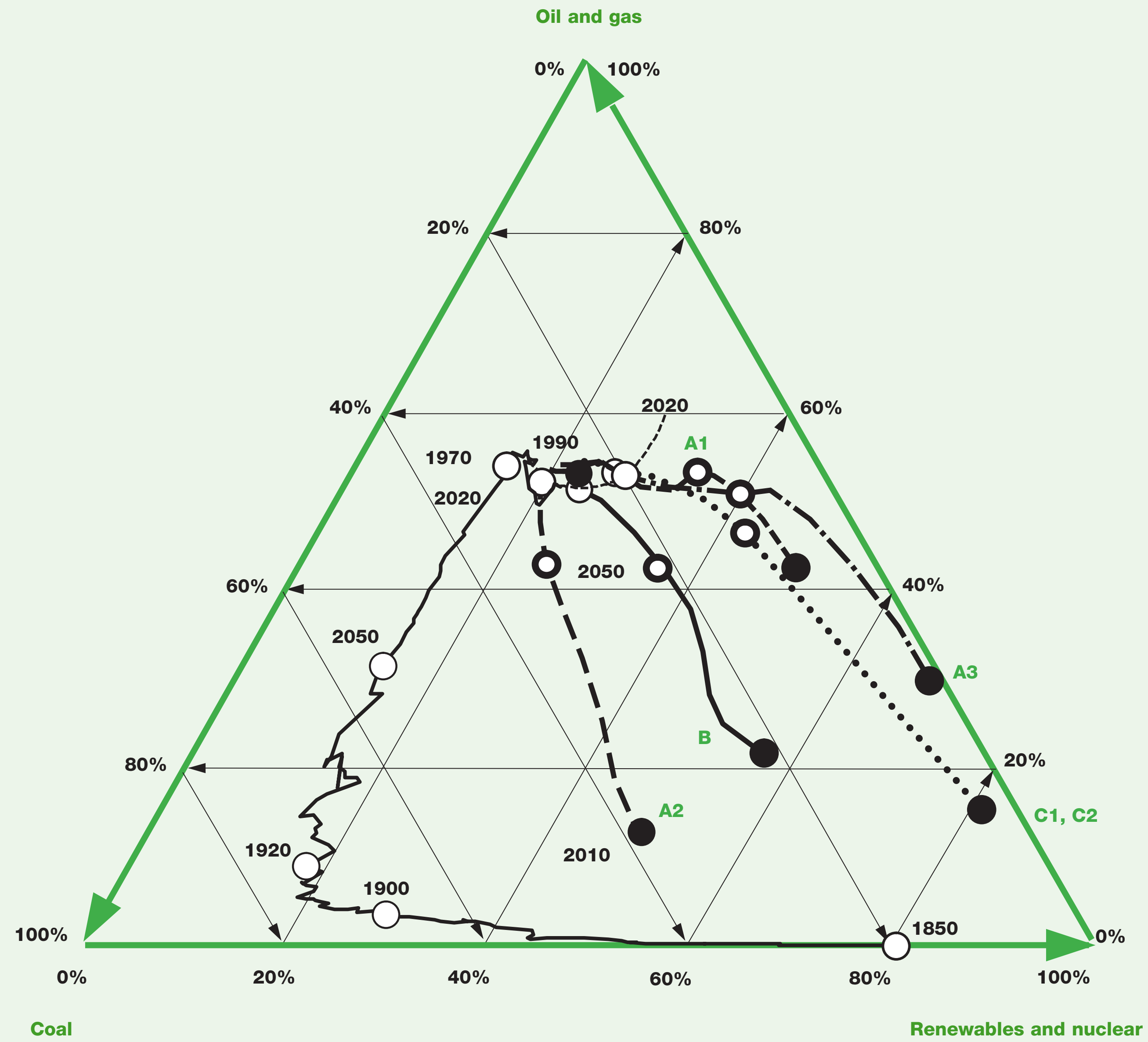
The figure also shows the wide range of future energy requirements for other scenarios in the literature. The vertical line that spans the scenario range in 1990 indicates the uncertainty across the literature of base-year energy requirements. The insert shows global population growth, 1850–2000, and projections to 2100. *Source: Nakićenović, Grübler, and McDonald, 1998; Morita and Lee, 1998; Nakićenović, Victor, and Morita, 1998; Bos and Vu, 1994.*

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.

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

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: Nakićenović, Grübler, and McDonald, 1998.

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.

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.

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.

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.

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.

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

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 (Grübler, 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.

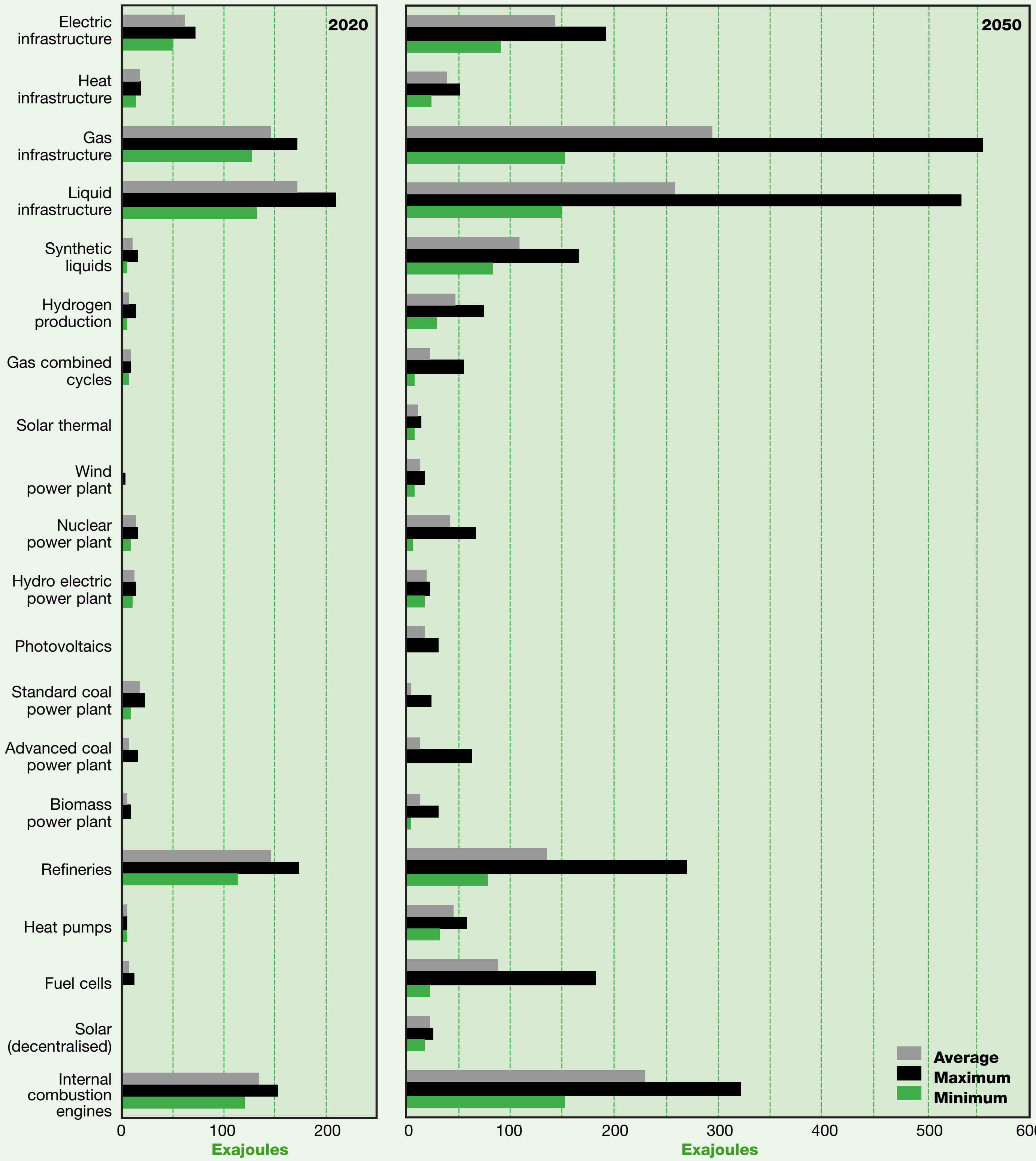
As noted above, technological progress has a price—it requires continual investment in RD&D. All the technological improvements in the scenarios that are reflected in the expansion of all technology categories shown in figure 9.5 presume steady RD&D investment. Given the importance of strategic investment 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,

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: Nakićenović, Grübler, and McDonald, 1998.

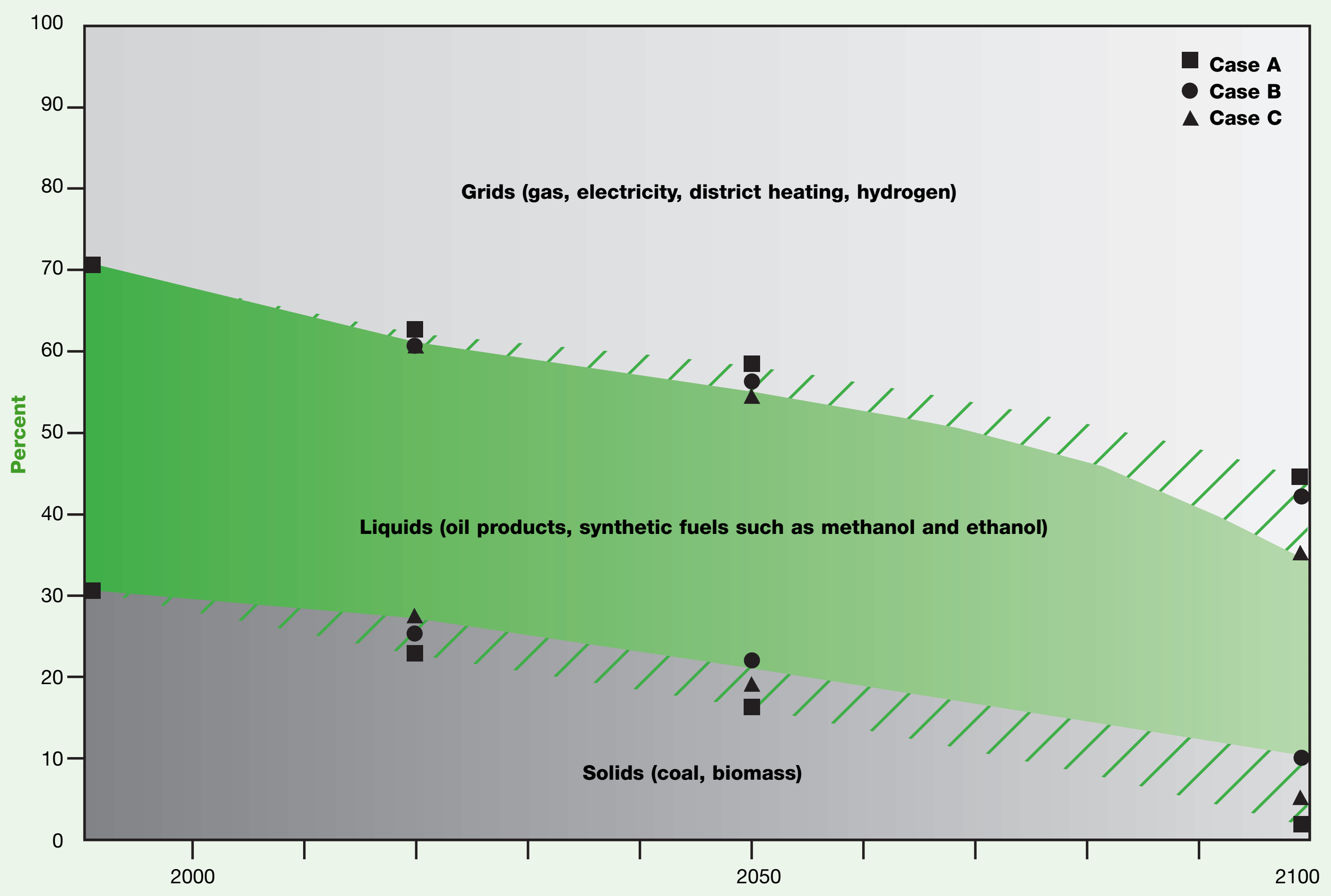
inefficient technologies are replaced by more efficient ones, and the structure of the energy-supply system and patterns of energy services change. These factors reduce the amount of primary energy needed per unit of final energy delivered to end users, as well as final energy per unit energy service. 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.

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

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: Nakićenović, Grübler, and McDonald, 1998.*

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

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.

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).

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 Sørensen, 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 (Sørensen, 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.

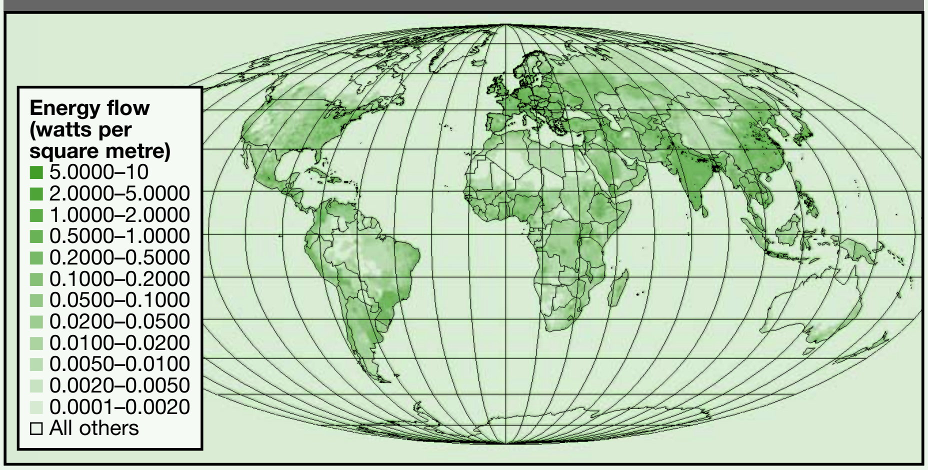
Most sustainable energy scenarios envisage a fundamental change in the future from today's inequitable distribution of benefits and adverse impacts. The scenarios use various methods to implement policies to move global development towards sustainability. For example, the IIASA-WEC case C scenarios assume 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

BOX 9.2. SPATIAL SCENARIO OF ENERGY END USE

Sørensen, 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. Sørensen, 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: Sørensen, Juemmel, and Meibom, 1999.

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* (Nakićenović 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.

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

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 (Nakićenović 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; Nakićenović and others, 2000; and Nakićenović, 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.

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.

Technological diffusion occurs over a long period of time, from a new technology's first introduction to its pervasive adoption.

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.

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.

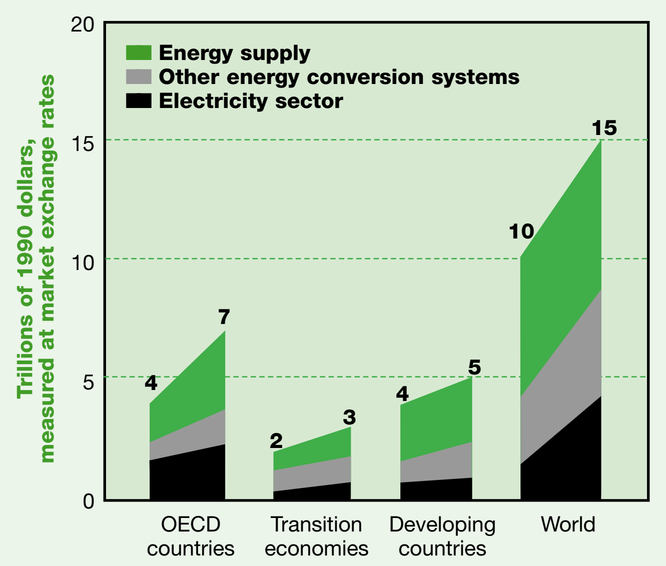
Very few scenarios in the literature give a detailed account of energy-related investments. Even fewer describe investments that will promote sustainable energy futures. Thus estimates of global capital requirements for energy development are often based on back-of-the-envelope calculations of aggregate 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

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: Nakićenović, Grübler, and McDonald, 1998.*

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.

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 Grübler, 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.

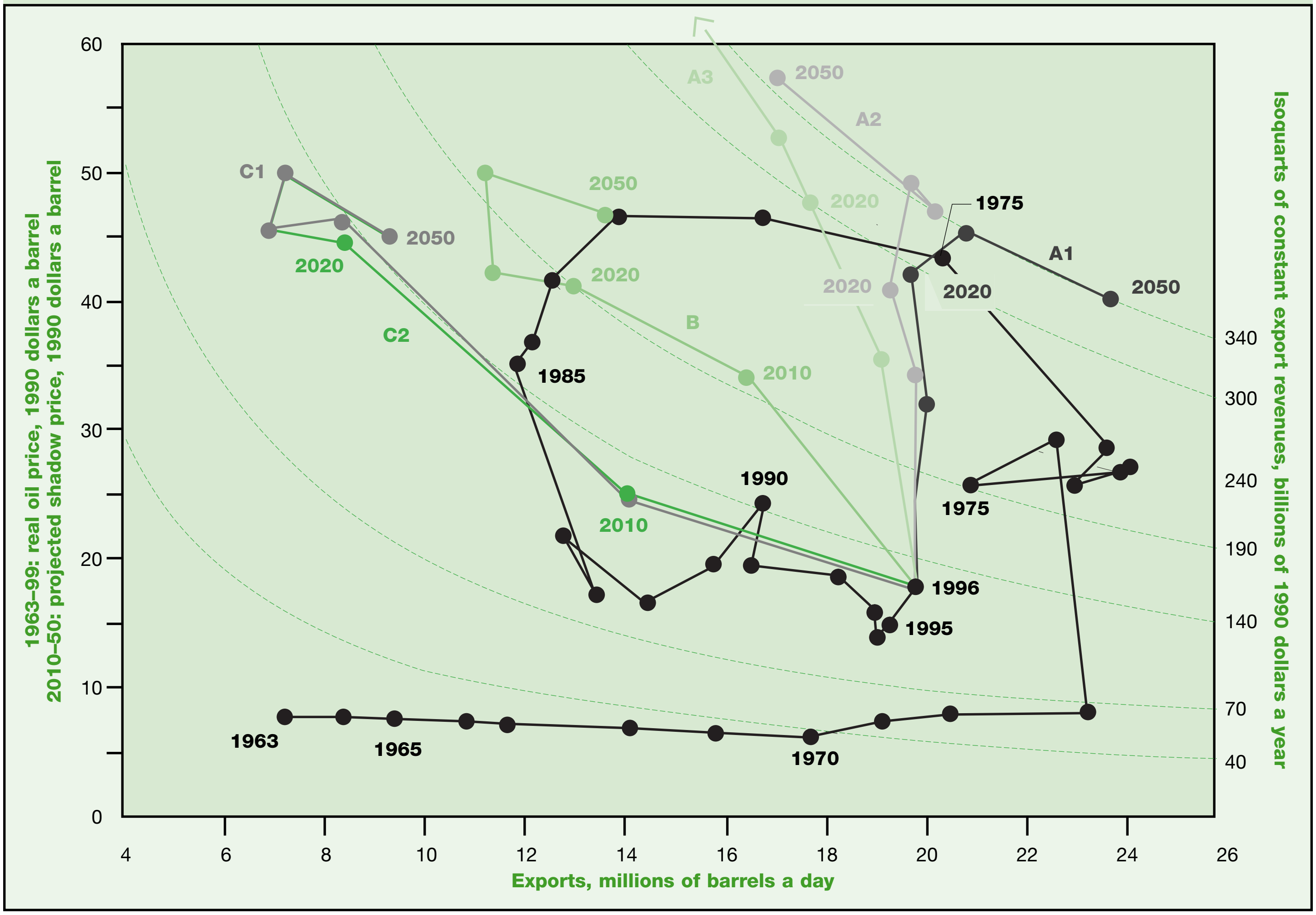
Technology costs and performance—including energy efficiency in particular—improve with experience, and there is a common pattern to such improvements for most technologies. This pattern of increasing returns to diffusion and transfer is important for the transition to sustainable energy futures, and 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 (Nakićenović, Grübler, 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: Nakićenović, Grübler, 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.

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.

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.

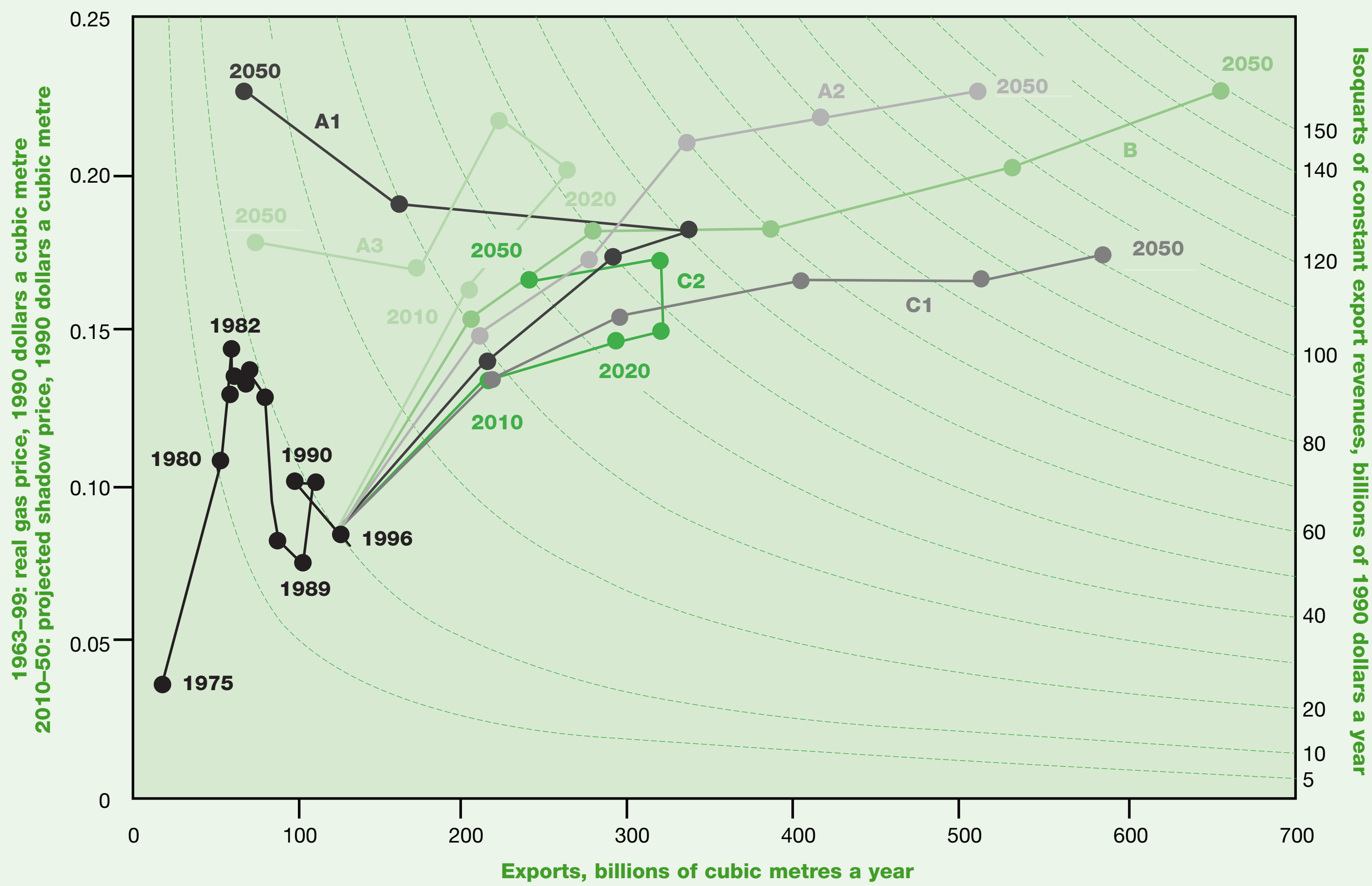
Both scenarios are characterised by declining energy sector investments as a share of GDP, to 2.3–3.0 percent by 2050. In absolute terms the cumulative financing requirements between 2000 and 2020 are in the range of $500–$700 billion.

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.

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

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



Source: Nakićenović, Grübler, and McDonald, 1998.

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.

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

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.

would be reduced to well below current levels.

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 Grübler (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

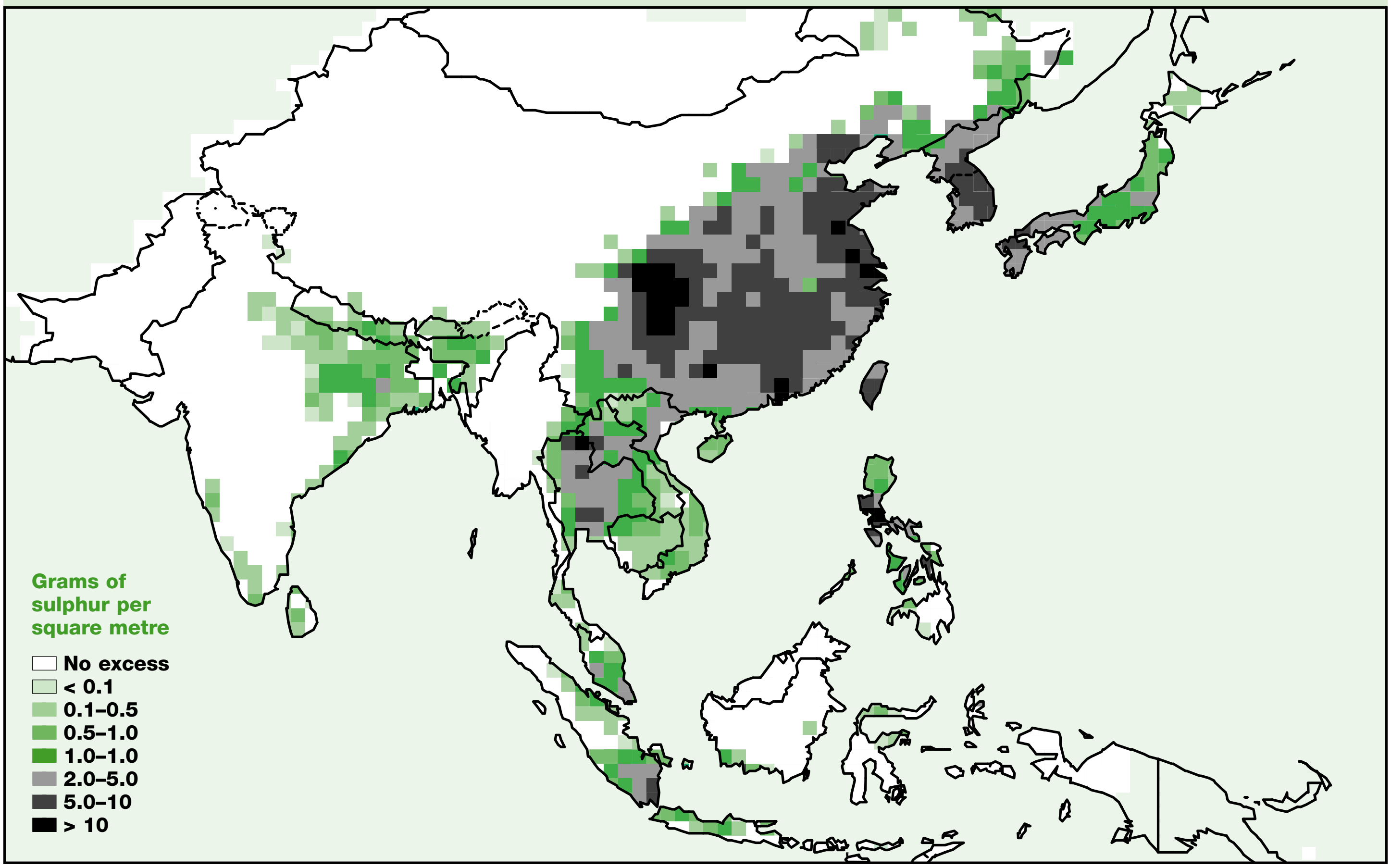
One important implication of the varying pattern of particulate and sulphur emissions across the scenarios is that the historically important, but uncertain, negative radiative forcing of sulfate aerosols may decline in the very long run (Hulme, 1997; chapter 3). This means that the current cooling effect 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), Nakićenović, Grübler, and McDonald (1998), Nakićenović (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.

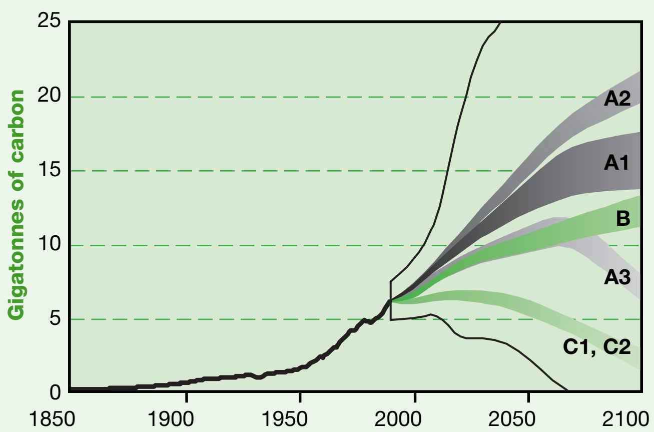
For the scenarios in the literature, the distribution of emissions by 2100 is very asymmetrical and portrays a structure resembling a trimodal frequency distribution: those with emissions of more than 30 gigatonnes of carbon (20 scenarios), those with emissions of 12–30 gigatonnes of carbon (88 scenarios), 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

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: Nakićenović, Grübler, and McDonald, 1998; Morita and Lee, 1998.

accordance with the United Nations Framework Convention on Climate Change (UNFCCC, 1992).

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.

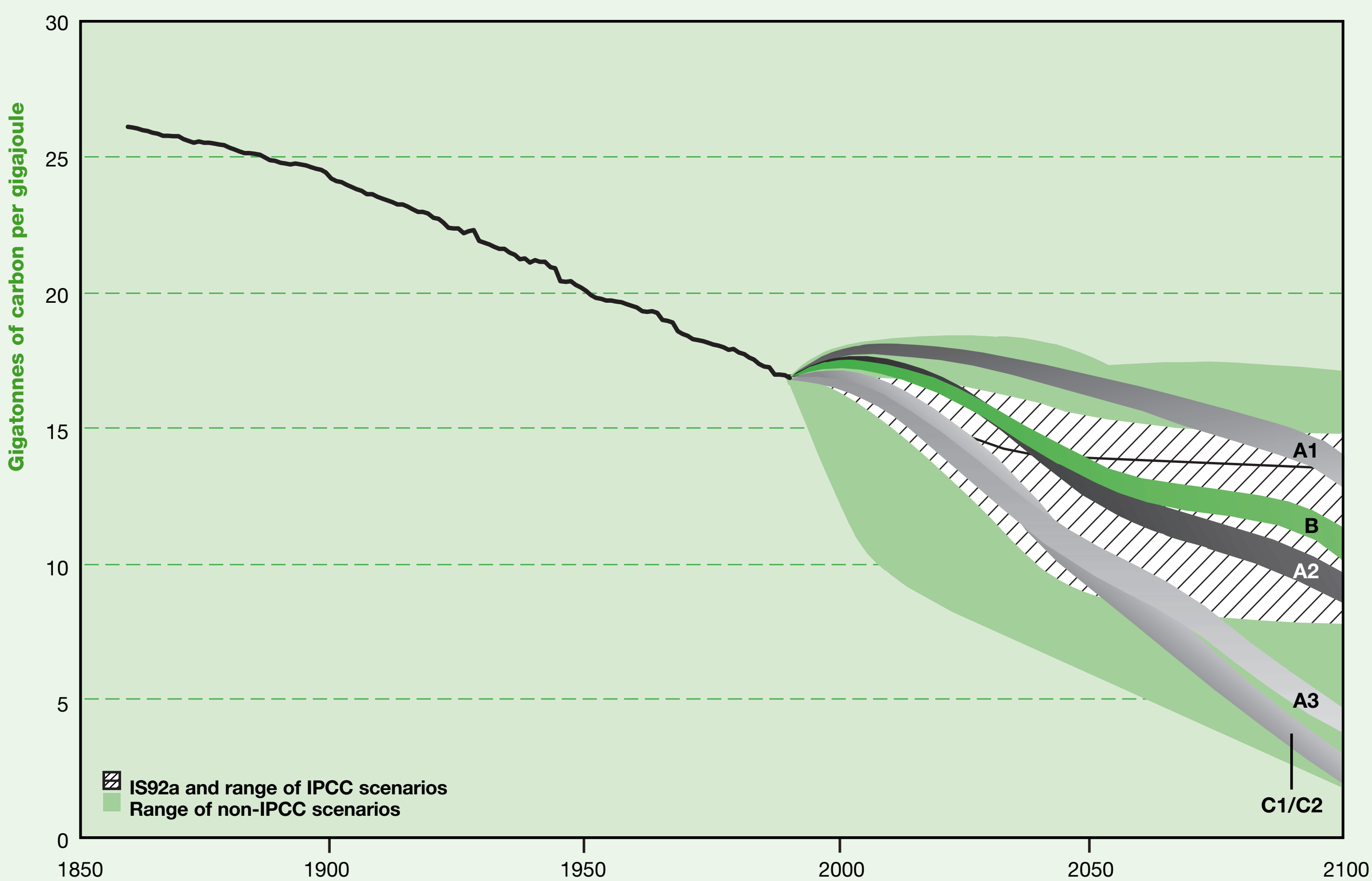
Another interpretation is that a given combination of driving forces is not sufficient to determine future emission paths. A particular combination of forces, such as those specified in the three IIASA-WEC case A scenarios, is associated with a whole range of possible emission paths. These three A scenarios 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.

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

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.

Furthermore decarbonisation also means that other environmental impacts tend to be lower (Nakićenović, 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

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: Nakićenović, Grübler, and McDonald, 1998.

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.

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 (Nakićenović, Grübler, 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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