Global Energy
Perspectives

Edited by
Nebojša Nakićenović, Arnulf Grübler, and Alan McDonald

IIASA
International Institute for
Applied Systems Analysis

World Energy Council
CONSEIL MONDIAL DE L'ENERGIE

Editors:
Nebojša Nakićenović
Arnulf Grübler
Alan McDonald

Lead Authors:
Arnulf Grübler
Michael Jefferson
Nadejda Makarova
Alan McDonald
Sabine Messner
Nebojša Nakićenović
Hans-Holger Rogner
Leo Schrattenholzer
Manfred Strubegger

Contributing Authors:
Markus Amann
Günther Fischer
Andrii Gritsevskyi
Hisham Khatib

Study Chair:
Nebojša Nakićenović

Steering Group:
Martin Bekkeheien
Klaus Brendow
Peter E. de Jánosi
Ian D. Lindsay†
John S. Foster
Jean-Romain Frisch
Michael Jefferson
Gordon J. MacDonald
Gerhard Ott
Keiichi Yokobori

Regional Coordinators:
José Luiz Alquéres
Richard E. Balzhiser
Klaus Brendow
Claude Destival
Yoichi Kaya
Hisham Khatib
Steve J. Lennon
Rajendra K. Pachauri
Yuan Shuxun

Contents

Preface

This book presents the results of a five-year study conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC). IIASA and WEC both have a 20-year history in analyzing energy futures. Starting with the 1981 study *Energy in a Finite World* (Häfele, 1981), IIASA has gained distinction for its research on the interactions between energy systems and the environment. WEC is well-known for its influential series of global energy perspectives culminating in the 1993 Commission Report *Energy for Tomorrow's World* (WEC, 1993).

The starting point for the study was the three alternative cases and one variant of future economic and energy development presented in *Energy for Tomorrow's World*. There, the principal analysis covered the period through 2020 with some extensions to 2100. This study describes three cases of alternative energy futures that diverge into a total of six scenarios and their implications for 11 world regions. The objective of this study was to examine more thoroughly the period beyond 2020, where the real potential for change lies. The goals were to integrate the near-term strategies through 2020 with the long-term opportunities to 2050 and beyond; to analyze alternative futures with a unified methodological framework using formal models and databases to ensure consistency and reproducibility; to incorporate a dynamic treatment of technological change; to harmonize regional aspirations with global possibilities; and to take account of new data and changes since 1993.

The study was conducted in two phases. The first phase, from 1993 to 1995, developed the six scenarios for the 11 world regions and analyzed their implications. It involved a core modeling team and approximately 50 additional experts, amounting to 10 person-years of effort. The results were presented in the 1995 IIASA–WEC report *Global Energy Perspectives to 2050 and Beyond*. The second phase, from 1995 to 1998, was devoted to an extensive review of the study assumptions, results, and implications for the 11 world regions. Teams of regional experts and reviewers, totaling over 100 individuals, were convened to provide more thorough regional assessments and alternative perspectives. Subsequently, the findings of this review process were incorporated into the scenarios and are reflected in their implications. The more specific regional perspectives are presented in Chapter 7. The results are thus a unique view of the future that offers both long-term global perspectives and more detailed regional realities and assessments. More detailed information about the data and quantitative findings of the study are available on the Internet (see Appendix E).

We believe that the issues addressed by this study are vital. An understanding of long-term energy perspectives, and how near-term decisions can expand or narrow the range of future opportunities, is essential if we are to build a future that is more prosperous and more equitable. We know of no other study that integrates long-term perspectives, near-term energy strategies, their implications, detailed modeling, and a broad range of regional assessments into one unified framework. IIASA and WEC are to be commended for their foresight and dedication in sponsoring such studies. No analysis can ever turn an uncertain future into a sure thing. However, we believe the study has identified patterns that are robust across a purposefully broad range of scenarios and regional perceptions.

This study has benefited from the experience and earlier work of both organizations on global energy perspectives. Some of this earlier work was only possible with external support for which we are grateful. We deeply appreciate the contributions of all authors to the analysis that made the study possible and for their contributions to numerous drafts of the book. It is a pleasure to also thank others who made the study possible: the members of the steering group who guided the study and the regional experts and reviewers, listed in Appendix D, for providing the regional perceptions and assessments that helped shape the final study findings. We would also like to acknowledge other colleagues at IIASA and WEC who provided assistance and support during the long process of conducting the analysis and drafting the book. In addition, we thank our colleagues in IIASA's Publications Department for the preparation of the manuscript.

Finally a personal note. This book is the product of a closely cooperating, interdisciplinary, and multinational team. Consequently, the authorship of various chapters is sometimes diffuse and individual authors cannot be held responsible for all the views and the opinions expressed in the study. And while there are many who can share in the credit for the study's successes and insights, the responsibility for any shortcomings or errors in the analysis as a whole and its presentation in this book are solely mine.

Nebojša Nakićenović
Project Leader
Environmentally Compatible Energy Strategies
International Institute for Applied Systems Analysis (IIASA)
A-2361 Laxenburg, Austria
naki@iiasa.ac.at

Summary

It is easier to anticipate the forms in which energy will be demanded by consumers in the future than to estimate the absolute level of energy demand, or which energy sources will supply that demand. With increasing per capita incomes around the world, people will demand higher levels of more efficient, cleaner, and environmentally less obtrusive energy services. Thus, we believe we see reasonably clearly the direction in which energy consumers are headed. However, the question of what kind of companies will supply energy services, and how, is wide open.

That is the central message of the three cases, subdivided into six scenarios, presented in this report. They cover a wide range of global energy developments – from a tremendous expansion of coal production to strict limits, from a phaseout of nuclear energy to a substantial increase, from carbon emissions in 2100 that are only one-third of today's levels to increases by more than a factor of three. Yet, for all the variation explored, all alternatives managed to match the expected demand pull for more flexible, more convenient, and cleaner forms of energy. The odds are thus good that consumers will indeed get what they want – flexibility, convenience, and cleanliness. Who their suppliers will be, and which energy sources will be tapped, depends on economic development in the world, on progress in science and technology, and on policies and institutions. And it depends very much on which suppliers make the near-term decisions that prove most effective in pairing up their services with evolving consumer preferences.

The six scenarios build both on the analysis presented in the IIASA–WEC study report *Global Energy Perspectives to 2050 and Beyond* published in 1995 and on the WEC Commission Report *Energy for Tomorrow's World* published in 1993. These studies concluded that, at least through 2020, the world will have to rely largely upon fossil fuels, with relatively few opportunities for alternatives. The results presented here reinforce this earlier conclusion – all six scenarios look much the same through 2020, and all rely heavily on fossil fuels. But after 2020, the six scenarios start to diverge.

Part of that divergence will depend on policy choices and development strategies. For example, two scenarios that assume dynamic, progressive international cooperation focused on environmental protection and international equity lead to less fossil fuel use than other scenarios. Most of the post–2020 divergence will depend on technological developments, industrial strategies, and consumer choice. Which energy sources will best match consumers' preference for flexible, more convenient, and cleaner energy services? Which companies will have made the investments in research, development, and demonstration (RD&D) that will give them a technological edge? Which will have refocused their businesses from providing just tons of coal or kilowatt-hours of electricity, to providing convenient and clean energy services to consumers?

The answers to those questions will be determined 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 in our scenarios prior to 2020, but the seeds of the post–2020 world will have been sown by then. The choice of the world's post–2020 energy systems may be wide open now. It will be a lot narrower by 2020.

World energy needs will increase

World population is expected to double by the middle of the 21st century, and economic development needs to continue, particularly in the South. According to the scenarios of this study, this results in a 3- to 5-fold increase in world economic output by 2050 and a 10- to 15-fold increase by 2100. By 2100, per capita income in most of the currently developing countries will have reached and surpassed the levels of today's developed countries. Disparities are likely to persist, and despite rapid economic development, adequate energy services may not be available to everyone, even in 100 years. Nonetheless the distinction between "developed" and "developing" countries in today's sense will no longer be appropriate. Primary and final energy use will grow much less than the demand for energy services due to improvements in energy intensities. We expect a 1.5- to 3-fold increase in primary energy requirements by 2050, and a 2- to 5-fold increase by 2100.

Energy intensities will improve significantly

As individual technologies improve, conversion processes and end-use devices progress along their learning curves, and as inefficient technologies are retired in favor of more efficient ones, the amount of primary energy needed per unit of economic output – the energy intensity – decreases. Other things being equal, the faster the economic growth, the shorter the obsolescence time, the higher the turnover of capital, and the greater the energy intensity improvements. In the six scenarios of this study, improvements in individual technologies are varied across a range derived from historical trends. Combined with the economic growth patterns of the different scenarios, the average global reductions in energy intensity range between

0.8% per year and 1.4% per year. These bracket the historical rate of approximately 1% per year and cumulatively lead to substantial energy intensity decreases. Some regions improve faster, especially where current intensities are high and economic growth and capital turnover are rapid.

Resource availability will not be a major global constraint

The resource scarcity perceived in the 1970s did not occur as originally assumed. With technological and economic development, estimates of the ultimately available energy resource base will continue to increase. A variety of assumptions about the timing and extent of new discoveries of fossil energy reserves and resources (conventional and unconventional), and about improvements in the economics of their recoverability, are reflected in the range of scenarios reported here. All, however, indicate that economic development over the next century will not be constrained by geological resources. Regional shortages and price increases can occur, due to the unequal distribution of fossil resources, but globally they are not a constraint. Environmental concerns, financing, and technological needs appear more likely sources of future limits. The short-term volatility of international politics, speculation, and business cycles will periodically upset the long-term expansion of resources.

Quality of energy services and forms will increasingly shape future energy systems

The energy system is service driven, from consumer to producer, while energy flows are resource and conversion-process driven, from producer to consumer. The scenarios demonstrate the need to consider energy end use and energy supply simultaneously, both from an analytical and a policy perspective. In addition to prices and quantities, energy *quality* matters increasingly. Quality considerations include convenience, flexibility, efficiency, and environmental cleanliness. The energy system is end-use driven. Under market liberalization, special competitive advantages will arise for those companies prepared to deliver a full range of energy services beyond just fuels and electricity.

Energy end-use patterns will converge, even as energy supply structures diverge

The six scenarios indicate that the historical drive toward ever more convenient, flexible, and clean fuels reaching the consumer can continue for a wide range of possible future energy supply structures. In all scenarios there is a shift toward electricity and toward higher-quality fuels, such as natural gas, oil products, methanol, and, eventually, hydrogen. In contrast to these converging trends, primary energy supply structures diverge, particularly after 2020. Fossil sources continue to provide most of the world's energy well into the next century but to a varying extent across the scenarios. There is a shift away from noncommercial and mostly unsustainable uses of biomass, and direct uses of coal virtually disappear. Sustainable uses of renewables including modern biomass come to hold a prominent place in all scenarios. They reach the consumer as electricity, liquids, or gases, rather than as solids.

Technological change will be critical for future energy systems

Technological change drives productivity growth and economic development. Across all scenarios the role of technological progress is critical. But progress has a price. RD&D of new energy technologies and the accumulation of experience in niche markets require upfront expenditures of money and effort. These are increasingly viewed as too high a price to pay in liberalized markets where the maximization of short-term shareholder value generally takes precedence over longer-term socioeconomic development and environmental protection. Yet, it is the RD&D investments of the next few decades that will shape the technology options available after 2020. A robust hedging strategy focuses on generic technologies at the interface between energy supply and end use, including gas turbines, fuel cells, and photovoltaics. These could become as important as today's gasoline engines, electric motors, and microchips.

Rates of change in global energy systems will remain slow

Capital turnover rates in end-use applications are comparatively short – one to two decades. Therefore, pervasive changes can be implemented rather quickly, and missed opportunities may be revisited. Conversely, the lifetimes of energy supply technologies, and particularly of infrastructures, are five decades or longer. Thus, at most one or two replacements can occur during the time horizon of this study. Betting on the wrong horse will have serious, possibly irreversible consequences. The RD&D and investment decisions made now and in the immediate future will determine which long-term options become available after 2020 and which are foreclosed. Initiating long-term changes requires action sooner rather than later.

Interconnectivity will enhance cooperation, systems flexibility, and resilience

Despite energy globalization, *market exclusion* remains a serious challenge. To date, some two billion people do not have access to modern energy services due to poverty and a lack of energy infrastructures. Many regions are overly dependent on a single, locally available resource, such as traditional fuelwood or coal, and have limited access to the clean flexible energy forms required for economic and social development. Policies to deregulate markets and get "prices right" ignore the poor.

Even the best functioning energy markets will not reach those who cannot pay. To include today's poor in energy markets, poverty must be eradicated, and that requires policy action that goes beyond energy policies alone. What energy policies can accomplish is the improvement of old infrastructures – the backbone of the energy system – and the development of new ones. New infrastructures are needed in Eurasia, in particular, to match the large available resources of oil and gas in the Caspian region and Siberia with the newly emerging centers of energy consumption in Asia. Extended interconnections are also needed in Latin America and Africa. Governments and industry need an expanded spirit of regional cooperation and a shared commitment to infrastructure investments now if benefits are to accrue in the long term.

Capital requirements will present major challenges for all energy strategies

For all scenarios the capital requirements of the energy sector are large, but not infeasible. Although investment requirements expand more slowly than overall economic growth, the energy sector will have to raise an increasing fraction of its capital from the private sector. It will face stiffer competition and return-on-investment criteria than it has in the past. Moreover, the greatest investment needs are in the now developing world, where current trends in the availability of both international development capital and private investment capital are not auspicious. How available capital is best mobilized remains a critical issue.

Regional differences will persist in global energy systems

Regional energy supply trends diverge across the scenarios even more than those at the global level due to differences in resource availability, trade possibilities, and national and regional development strategies. Regional development aspirations often exceed even the wide range of possibilities outlined by the six global scenarios analyzed here. Yet, for all their diversity, regional perspectives confirm the essential global conclusion: while a range of possible energy sources can fuel the future, there is a persistent trend toward cleaner, more convenient energy forms reaching the consumer. In all regions, success will depend on improved efficiency, continued technological progress, a favorable investment climate, free trade, and enhanced regional and international cooperation, particularly in shared energy infrastructures.

Local environmental impacts will take precedence over global change

The natural capacity of the environment to absorb higher levels of pollution, particularly in densely populated metropolitan areas, will become the limiting factor for the unconstrained use of fossil fuels. Local environmental problems are of greater concern to local decision makers than global problems and therefore will have a greater near-term impact on policy. In the developing world indoor air pollution is an urgent environmental problem. A shift away from cooking with wood in open fireplaces will reduce indoor pollution levels currently estimated to be 20 times higher than in industrialized countries. A second urgent problem is the high concentration of particulate matter and sulfur dioxide in many urban areas. Regional air pollution could also prove problematic, especially in the rapidly growing, densely populated coal-intensive economies of Asia. Without abatement measures, sulfur emissions could cause serious public health problems and subject key agricultural crops to acid deposition 10 times sustainable levels.

Decarbonization will improve the environment at local, regional, and global levels

The continuing shift to higher-quality fuels means a continuing reduction in the carbon content of fuels, that is, decarbonization of the energy system. Decarbonization means lower adverse environmental impacts per unit of energy consumed, independent of any active policies specifically designed to protect the environment. And at the global level, it translates directly into lower carbon dioxide emissions. But decarbonization is not enough – additional active policies will be required. In some cases energy and environmental policies are mutually reinforcing. Policies to reduce global carbon dioxide emissions, for example, also reduce acidification risks. In others, energy and environmental policies work at cross purposes. Restrictions on nuclear power, for example, mean a possibly greater dependence on fossil fuels, and vice versa. In all cases, however, more rapid technological improvement means quicker progress toward cleaner fuels, and cleaner fuels mean a cleaner environment.

Acronyms

Adv. Coal – advanced coal
AFR – Sub-Saharan Africa
bbl – barrels (oil equivalent, 1 toe = 7 bbl)
BIGSTIG – biomass integrated-gasifier steam-injected gas turbine
BLS – IIASA's Basic Linked System
BOO – build-own-operate
BOT – build-own-transfer
CC – combined cycle
CFCs – chlorofluorocarbons
CH_3OH – methanol
CH_4 – methane
CHP – combined heat and power generation
CIS – Commonwealth of Independent States
CO – carbon monoxide
CO_2 – carbon dioxide
CO2DB – IIASA's Carbon Dioxide Mitigation Technology Database
CPA – Centrally planned Asia and China
CPE – commercial primary energy
DCs – developing countries
DSM – demand-side management
EEU – Central and Eastern Europe
EIA – Energy Information Administration
EU – European Union
FAO – UN Food and Agriculture Organization
FBRs – fast breeder reactors
FCCC – Framework Convention on Climate Change
FSU – Newly independent states of the former Soviet Union
GATT – General Agreement on Tariffs and Trade
GDP – gross domestic product
GDP_{mer} – GDP calculated on the basis of market exchange rates
GDP_{ppp} – GDP calculated on the basis of purchasing power parities
GNP – gross national product
GtC – gigatons carbon
Gtoe – giga [billion (10^9)] tons oil equivalent
GW – gigawatts
GW_e – gigawatts electric
GWP – gross world product
H_2 – hydrogen
ha – hectares
HTFC – high temperature fuel cell
IEA – International Energy Agency
IGCC – integrated gasifier combined cycle

IIASA – International Institute for Applied Systems Analysis
IND – industrialized countries
IPCC – Intergovernmental Panel on Climate Change
IRP – integrated resource planning
kgoe – kilograms oil equivalent
kW$_e$ – kilowatts electric
kWh – kilowatt hours
LAM – Latin America and the Caribbean
LESS – Low CO$_2$-Emitting Energy Supply Systems
LNG – liquefied natural gas
LPG – liquefied petroleum gas
mbd – million barrels per day
MEA – Middle East and North Africa
mer – market exchange rate
MtC – megatons carbon
Mtoe – megatons oil equivalent
MtS – megatons sulfur
MW$_e$ – megawatts electric
N$_2$O – nitrous oxide
NAFTA – North American Free Trade Agreement
NAM – North America
NGL – natural gas liquids
NO$_x$ – nitrogen oxide
OECD – Organisation for Economic Co-operation and Development
OLADE – Latin American Energy Organization
OPEC – Organization of the Petroleum Exporting Countries
PAO – Pacific OECD
PAS – Other Pacific Asia
PE – primary energy
PM$_{10}$ – particulate matter less than 10 microns in diameter
ppl – power plants
ppmv – parts per million by volume
PSA – production sharing agreement
PV – photovoltaics
RAINS – IIASA’s Regional Acidification INformation and Simulation model
RD&D – research, development, and demonstration
REFs – reforming economies (EEU plus FSU)
SAS – South Asia
SG – Scenario Generator
SO$_2$ – sulfur dioxide
SO$_x$ – sulfur oxide
tC – tons carbon
tce – tons coal equivalent
toe – tons oil equivalent
TPE – total primary energy
tU – tons uranium
TW$_e$ – terawatts electric
TWh – terawatt hours
UN – United Nations
UNCED – United Nations Conference on Environment and Development
UNDP – United Nations Development Programme
VOC – volatile organic compound
WEC – World Energy Council
WEU – Western Europe
WHO – World Health Organization

Chapter 1

Introduction

This study examines long-term energy perspectives, their constraints, and opportunities by formulating scenarios. A scenario is a narrative, in this case with illustrations and quantitative characteristics, describing one possible way the future might unfold. As discussed in *Box 2.1*, it is not a prediction or a forecast. Nor is it just any narrative. It has to be an internally consistent and reproducible narrative, which means checking to make sure all the numbers add up. This is done largely with formal models. The formal models used for this study are described briefly in Appendix A on methodology. In the analysis and modeling work, the countries of the world were grouped into 11 different regions. The groupings are shown in *Figure 1.1* and discussed in *Box 1.1*. A detailed listing is given in Appendix B.

To draw robust conclusions, we need to formulate a range of scenarios covering very different possible futures. Each must be internally consistent, as checked by the formal models, and each must be reproducible and plausible to someone exercising open-minded, but realistic, judgment. If there are common tendencies across very different scenarios, those provide one useful set of analytic conclusions. And if there are discernible connections between the long-term divergence among scenarios and differences in their near-term policy or investment actions, those form another useful set of conclusions. In this study the scenarios provided conclusions of both sorts.

Chapter 2 lays out the scenarios and, in particular, how they were put together to purposely cover a broad range of possible futures. There are six scenarios grouped into three cases, Cases A, B, and C. The definition of cases came before the definition of scenarios, and the three cases are based on the three cases presented in *Energy for Tomorrow's World* (WEC, 1993) and *Global Energy Perspectives to 2050 and Beyond* (IIASA–WEC, 1995). Each is summarized in Chapter 2. Case A is basically a high-growth future in terms of income, energy, and technology. Case B has more modest but perhaps more realistic growth. Case C assumes

Box 1.1: World regions

The analysis and modeling work underlying the scenarios developed within this study was done for 11 world regions (for their definition see map below and Appendix B), which follow the regional detail of IIASA–WEC, 1995.

In this report some results are presented at the level of three "macroregions" and others for all 11 study regions. The macroregions are the former centrally planned economies now in the process of economic reform (REFs, in shades of blue in *Figure 1.1*), the developing countries (DCs, in shades of green), and a group that approximates the Organisation for Economic Co-operation and Development (OECD, in shades of red and orange). Developing countries are sometimes referred to in the text as the "South" to distinguish them from the industrialized regions of the "North" (i.e., OECD and REFs).

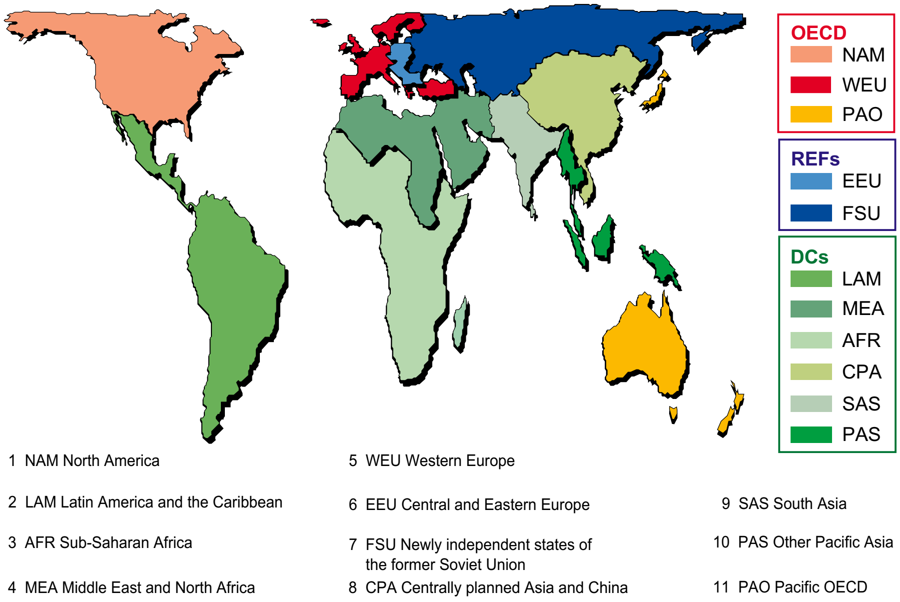


Figure 1.1: IIASA–WEC study regions.

dynamic progressive international cooperation focused on environmental protection and international equity. Energy use in Case C is the lowest of the three cases, but economic and technological growth are higher than in Case B. As the study proceeded, it became apparent that more variety was needed than was represented by the three basic cases. Case A was therefore subdivided into three alternative scenarios (A1, A2, and A3), and Case C into two alternatives (C1 and C2). The six scenarios are all introduced in Chapter 2 and are based on the analysis presented in *Global Energy Perspectives to 2050 and Beyond* (IIASA–WEC, 1995).

All three cases – all six scenarios – start from the base year 1990 and the historical developments leading up to that year. Chapter 3 reviews the empirical basis for the study in terms of historical changes and tendencies. It emphasizes current disparities around the world in income, economic structure, energy use, and energy intensity, and compares them with variations over time in individual countries. The chapter also presents the basic interpretation of past data that underlies our extensions of historical tendencies and structural transformations into the future in the different cases. Finally, it summarizes key developments that have taken place since the base year, 1990.

Chapter 4 looks at the determinants of future energy use and describes how they vary across the six scenarios. The presentation is divided into six headings: population growth, economic growth, energy intensity improvements, technological change, the resource base, and environment.

Chapter 5 presents the essential quantitative characteristics of all six scenarios using many illustrations. It describes how they differ in their primary energy structures, their resource use, their electricity sectors, and their final energy use.

Chapter 6 turns to important implications on a number of fronts: investments and financing, international trade, costs, technology, the constraints and opportunities facing different energy industries (coal, oil, gas, renewables, and nuclear), and environmental impacts at the local, regional, and global levels.

Chapter 7 presents scenario developments and findings for each of the 11 study regions and compares them with the global picture provided by Chapter 5. Chapter 7 also presents a summary of regional expert reviews – a unique feature of this study. Detailed regional reviews provide a “bottom-up” interpretation of the “top-down” global scenario analysis. This sets the stage for evaluating and comparing regional aspirations with global possibilities and provides a final test of the consistency of the global and regional findings. The chapter also summarizes the range of energy-related concerns across regions as identified in a detailed poll of World Energy Council (WEC) regional experts.

In Chapter 8, we come to conclusions – of both types mentioned at the beginning of this chapter. First, there are some pervasive developments across all scenarios and in most regions. We believe strategies that take such developments carefully into account will benefit no matter how the future turns out. Second, there are also apparent connections between near-term strategies and the different futures of the scenarios. Particular near-term strategies improve the odds of particular long-term futures. Chapter 8 lays out these conclusions and relates them to near-term decisions. It identifies future opportunities and how best to exploit them. Finally, the chapter gives a different, visual interpretation of the scenarios.

Chapter 2

An Overview of Scenarios

This study presents three cases of future developments subdivided into six alternative scenarios (see *Box 2.1* for a discussion of scenarios). The principal focus is on the period between 2020 and 2050, but some results are also presented out to 2100. In brief, Case A presents a future of impressive technological improvements and consequent high economic growth. Case B describes a future with less ambitious, though perhaps more realistic, technological improvements, and consequently more intermediate economic growth. Case C presents a "rich and green" future. It includes both substantial technological progress and unprecedented international cooperation centered explicitly on environmental protection and international equity. Key characteristics of the three cases are given in *Table 2.1*. The following paragraphs provide details on what the scenarios have in common and where they differ.

2.1. Commonalities

All three cases provide for substantial social and economic development, particularly in the developing world. They provide for improved energy efficiencies and environmental compatibility, and thus for associated growth in both the quantity and quality of energy services. Across all three cases, the structure of final energy develops in the same way 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 (10^9) by 2050 and to nearly 12 billion by 2100. All have been checked for internal consistency with the aid of formal models and through a lengthy regional expert review process.

Table 2.1: Summary of the three cases in 2050 and 2100 compared with 1990.

	Case		
	A High growth	B Middle course	C Ecologically driven
Population, billion			
1990	5.3	5.3	5.3
2050	10.1	10.1	10.1
2100	11.7	11.7	11.7
GWP, trillion US(1990)$			
1990	20	20	20
2050	100	75	75
2100	300	200	220
Global primary energy intensity improvement, percent per year	Medium	Low	High
1990 to 2050	–0.9	–0.8	–1.4
1990 to 2100	–1.0	–0.8	–1.4
Primary energy demand, Gtoe			
1990	9	9	9
2050	25	20	14
2100	45	35	21
Resource availability			
Fossil	High	Medium	Low
Non-fossil	High	Medium	High
Technology costs			
Fossil	Low	Medium	High
Non-fossil	Low	Medium	Low
Technology dynamics			
Fossil	High	Medium	Medium
Non-fossil	High	Medium	High
Environmental taxes	No	No	Yes
CO_2 emission constraint	No	No	Yes
Net carbon emissions, GtC			
1990	6	6	6
2050	9–15	10	5
2100	6–20	11	2
Number of scenarios	3	1	2

Abbreviations: GWP = gross world product; Gtoe = gigatons oil equivalent; CO_2 = carbon dioxide; GtC = gigatons of carbon.

Box 2.1: Scenarios: Alternative views of the future

In designing scenarios we devise images of the future, or better of alternative futures. Scenarios are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future could unfold. Each is based on an internally consistent and reproducible set of assumptions about key relationships and driving forces of change that is derived from our understanding of both history and our current situation. Often scenarios are formulated with the help of formal models. Most scenarios, including those presented in this book, make one particular strong assumption about the future: the absence of major discontinuities and catastrophes. These are not only inherently difficult to anticipate, but also offer little policy guidance on managing an orderly transition from today's energy system, which relies largely on fossil fuels, toward a more sustainable system with more equitable access to energy services.

Scenarios can be both *descriptive* and *normative*. Descriptive scenarios outline possible developments in the absence of significant changes in policies, economics, or technology. Normative (or *prescriptive*) scenarios attempt to incorporate the consequences of specific modifications in current policies, institutions, and technologies. In the study reported here, Case B is a prime illustration of a descriptive scenario, while Case C is the prototype of a normative scenario. Case A contains both descriptive and normative elements.

2.2. Differences

2.2.1. Case A: "High Growth"

Case A presents a future designed around ambitiously high rates of economic growth and technological progress. It incorporates the conviction that there are essentially no limits to human technological ingenuity. Case A presumes favorable geopolitics and free markets. Economic growth runs about 2% per year in the OECD countries and is twice as high in the developing countries. High growth facilitates a more rapid turnover of capital stock and changes in economic structure, both of which spur efficiency improvements and technological progress. If Case A is extended all the way to 2100 – again with the heroic assumption of 100 years of favorable geopolitics – global average per capita income surpasses even the highest levels observed today, making the distinction between "developed" and "developing" regions in today's sense no longer appropriate.

Case A includes three scenarios that address key developments in energy supply. They vary principally in the future they envision for coal, on one side, and nuclear and renewables, on the other. In Scenario A1, there is high future availability of oil and gas resources. Dominance of oil and gas is perpetuated to the end of the 21st century. At the other end of the spectrum, Scenario A2 assumes oil and gas resources to be scarce, resulting in a massive return to coal. Finally, in Scenario A3 rapid technological change in nuclear and renewable energy technologies results in a phaseout of fossil fuels for economic reasons rather than due to resource scarcity.

Scenario A1 describes a case with no remarkable developments favoring either coal or nuclear. As a result, technological change focuses on tapping the vast potential of conventional and unconventional oil and gas occurrences. The result challenges conventional wisdom about the possible exhaustion of fossil resources. Indeed, they appear sufficient to allow a smooth, comfortable transition over the next century to alternative supply sources based on nuclear and new renewables matched with high-quality energy carriers in the form of electricity, liquids, gas, and later hydrogen. There is little need to resort to the "backstop" fossil fuel *par excellence* – coal. It continuously loses market share.

The world of Scenario A2 is one in which the greenhouse warming debate is resolved in favor of coal. The benefits of climate change and CO_2 fertilization prove to exceed the disadvantages. This leaves little policy incentive to phase out fossil fuels early, particularly in areas endowed with large, cheap coal resources. Sulfur and nitrogen emissions are mitigated through control technologies, and coal's vast resources make it the fossil fuel of choice. Coal also provides the "backstop" for dwindling resources of conventional oil and gas, which are assumed to be limited to currently known reserves and resources. With the depletion of open-cast coal deposits, significant technological challenges remain concerning ever deeper coal mines and the elaborate chemistry of converting coal to synliquids. *In situ* gasification and remote-controlled, robotic mining operations characterize a capital-intensive "coal economy."

We have labeled the future of Scenario A3 "bio-nuc." Large-scale renewables and a new generation of nuclear power lead a technology-driven transition to a post-fossil-fuel age. The market penetration dynamics of the transition match those characterizing the historical replacement of traditional 19th century energy forms by fossil fuels. Natural gas is the transitional fossil fuel of choice, and no challenges are imposed on the availability of economically competitive oil resources. Pressure to dig deeply into nonconventional fossils is limited. By 2100, there is an almost equal reliance on nuclear energy, natural gas, biomass, and a fourth category composed mostly of solar energy, but also containing wind and other "new" renewables.

2.2.2. Case B: “Middle Course”

Case B has a single scenario. It incorporates more modest estimates of economic growth and technological development, and the demise of trade barriers and expansion of new arrangements facilitating international exchange. Compared with the Case A scenarios (and the Case C scenarios), it is more “pragmatic,” which is its main appeal. Case B manages to fulfill the development aspirations of the South, but less uniformly and at a slower pace than in the other cases. For regions such as Africa, progress is painfully slow. Overall, economic growth rates to 2020 are more modest than in many studies with shorter time horizons, for example, Case B of *Energy for Tomorrow’s World* (WEC, 1993). This change reflects recent setbacks and slow economic restructuring in Eastern Europe, the former Soviet Union, and many developing countries. These short-term setbacks are, however, ultimately counterbalanced by higher growth rates in the long run.

Case B’s more modest energy demand and slower technology improvements result in the greatest reliance on fossil fuels of any of the scenarios, except the coal-intensive Scenario A2. Through the medium term, the structure of Case B’s energy supply and use remains much closer to the current situation than those of Cases A and C. Beyond 2020, however, the depletion of fossil resources without counterbalancing technological progress forces more dramatic changes in energy supply structures. Nonetheless, a transition away from fossil fuel use is feasible and manageable. Contrary to perceptions of imminent resource shortages, oil and gas maintain a significant share in the global primary energy mix up to about 2070 by moving into costlier categories of conventional and unconventional resources. Constraints prove to be based less on geology and more on financial and environmental considerations. As a scenario that might be characterized as “muddling through,” Case B inevitably contains features that are less attractive, though perhaps more realistic, than corresponding characteristics in the other cases.

2.2.3. Case C: “Ecologically Driven”

Case C is the most challenging. It is optimistic about technology and geopolitics, but unlike Case A, it assumes unprecedented progressive international cooperation focused explicitly on environmental protection and international equity. The future described by Case C includes a broad portfolio of environmental control technologies and policies, including incentives to encourage energy producers and consumers to utilize energy more efficiently and carefully, “green” taxes, international environmental and economic agreements, and technology transfer. It reflects substantial resource transfers from industrialized to developing countries, spurring growth in the South. These resource transfers reflect stringent international environmental taxes or incentives, which recycle funds from the OECD to developing countries. While economic output is less than in Case A, Case C still describes a positive-sum game relative to Case B, with a total GWP greater than in Case B and a significant reduction in present economic disparities.

Case C incorporates policies to reduce carbon emissions in 2100 to 2 GtC per year, one-third of today's level. One option is a carbon tax that gradually increases well above US$100 per ton of carbon (tC) in 2100 to a value comparable with average current gasoline taxes in Western Europe. The 2 GtC emission ceiling can also be imposed by command-and-control regulations, such as inflexible emission limits and mandated technologies, but model checks confirm that these create inefficiencies that show up in the form of higher and irregular costs (shadow prices) for emission reductions. Other policy alternatives also exist. In general, we believe that the more policies focus on carrots, rather than sticks – that is, the more they create incentives to change behavior and use more energy-efficient equipment, and the less they focus on penalties such as fines and taxes – the more likely consumers and industry are to respond positively and quickly.

In Case C, nuclear energy is at a crossroads. Two scenarios are included. They both meet the CO_2 emissions ceiling in 2100, but they describe two very different paths that nuclear power might take. In one path a new generation of nuclear reactors is developed (Scenario C2) that is inherently safe and small scale – 100 to 300 megawatts electric (MW_e) installed capacity – and that finds widespread social acceptability, particularly in areas of scarce land resources and high population densities that limit the potential supply from renewables. In the other (Scenario C1), nuclear power proves a transient technology that is eventually phased out entirely by the end of the 21st century.

Chapter 3

Global Energy Needs: Past and Present

Energy needs – in the past, for the present, and in the future – are driven by three principal factors: population growth, economic development, and technological progress. Each of these is addressed in Chapter 4. These driving forces develop in different, but internally consistent, ways in each of the six possible futures laid out in this report – the three Case A scenarios, the single Case B scenario, and the two Case C scenarios. For each case, it is important to understand how the three driving forces fit together and how they tie into historical developments leading up to today. We start, in this section, with some essential features from history.

3.1. Two Grand Transitions

Prior to the Industrial Revolution, the energy system relied on harnessing natural energy flows and animal and human power to provide required energy services in the form of heat, light, and work. Power densities and availability were constrained by site-specific factors, with mechanical energy sources limited to draft animals, water, and windmills. The only form of energy conversion was from chemical energy to heat and light – through burning fuelwood, for example, or tallow candles. Energy consumption typically did not exceed 0.5 tons oil equivalent (toe) per capita per year (Smil, 1994).

Two "grand transitions" have since shaped structural changes in the energy system at all levels. The first was initiated with a radical technological end-use innovation: the steam engine powered by coal. The steam cycle represented the first conversion of fossil energy sources into work; it allowed the provision of energy services to be site independent, as coal could be transported and stored as needed;

and it permitted power densities previously only possible in exceptional locations of abundant hydropower. Stationary steam engines were first introduced for lifting water from coal mines, thereby facilitating increased coal production. Later, they provided stationary power for what was to become an entirely new form of organizing production: the factory system. Mobile steam engines, on locomotives and steam ships, enabled the first transport revolution, as railway networks were extended to even the most remote locations and ships were converted from sail to steam. Characteristic energy consumption levels during the "steam age," approximately the mid-19th century in England, were about 2 toe per capita per year. By the turn of the 20th century, coal had replaced traditional non-fossil energy sources and supplied virtually all the primary energy needs of industrialized countries.

The second grand transition was the greatly increased diversification of both energy end-use technologies and energy supply sources. Perhaps the most important single innovation was the introduction of electricity as the first energy carrier that could be easily converted to light, heat, or work at the point of end use. A second key innovation was the internal combustion engine, which revolutionized individual and collective mobility through the use of cars, buses, and aircraft. Like the transition triggered by the steam engine, this "diversification transition" was led by technological innovations in energy end use, such as the electric light bulb, the electric motor, the internal combustion engine, and aircraft. However, changes in energy supply have been equally far-reaching. In particular, oil emerged from its place as an expensive curiosity at the end of the 19th century to occupy the dominant global position, where it has remained for the past 30 years.

Figure 3.1 (see also *Figure 5.4*) illustrates these two grand transitions by showing the changing shares of different primary energy sources in the global energy supply, including the long transition away from traditional renewable energy forms toward fossil fuels; the emergence and culmination of coal, which supplied close to two-thirds of global energy needs by the eve of World War I; the introduction of oil and, later, natural gas, first as a by-product of oil production and then as an energy carrier in its own right; the peak in the market share of oil in the 1970s; and finally a reduction in the dynamics of change in the primary energy supply structure during the past two decades. This reduced dynamism may be partly due to the increased regulatory interest received by the energy sector in recent decades, partly due to oil's attractiveness for the transportation sector, where demand has risen steadily, and partly due to the delayed switch in power generation away from coal and oil to natural gas.

The two grand transitions have made possible far-reaching structural changes in employment, the spatial division of labor, and international trade. These are associated with modernizing traditional economic and social structures, and include the following, in particular:

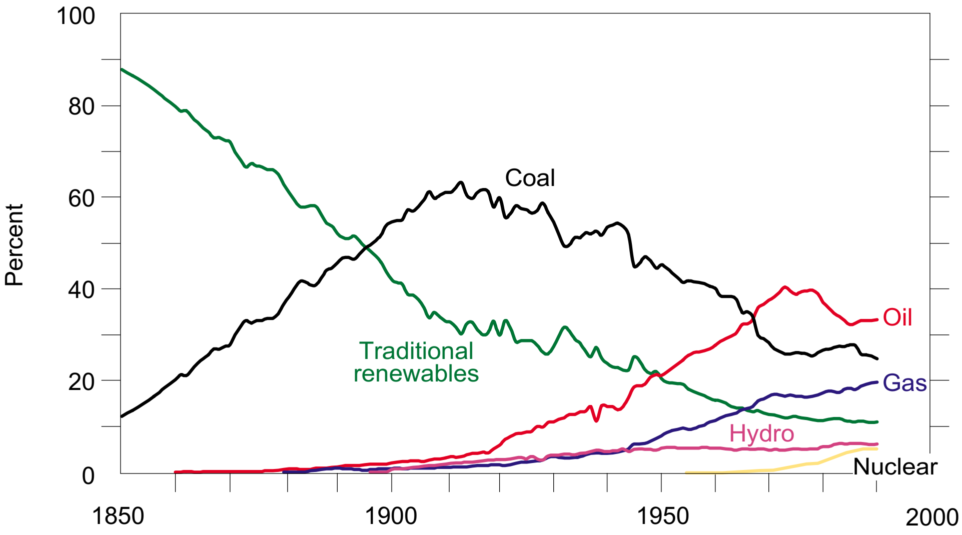


Figure 3.1: World primary energy shares from 1850 to 1990, in percent. Source: Nakićenović, 1984; updated using BP, 1995 and earlier volumes.

- *Industrialization:* Employment and value generation move progressively away from agriculture toward industry and manufacturing in particular. Subsequently there are structural shifts away from "smoke-stack" industries toward services and industries characterized by the increasing importance of information generation and handling.
- *Urbanization:* Spatially, urbanization implies a drastic relocation from rural to urban residence, employment, and economic activities. Socially, urbanization entails deep changes in the social fabric and the emergence of new values and lifestyles. Economically, urbanization is driven by the large and diverse economic *opportunities* that the agglomeration of many enterprises and consumers entails. As a result, the largest portion of a country's gross domestic product (GDP) is generated in urban areas and agglomerations. As an extreme case, it is estimated that 80% of the GDP of Indonesia is generated in the national capital. For energy, urbanization imposes strict quality requirements for the energy carriers used, including higher power density and cleanliness.

Important changes in energy demand and supply associated with these two grand transitions include the following:

- *Commercial energy:* There has been a transition from noncommercial to commercial energy forms that reflects the structural economic shift from agriculture to industry, the related monetarization of the economy, and increasing urbanization.

- *Increasing energy "quality":* There has also been a transition from direct use of solid energy forms, such as traditional biomass and coal, to liquids and grid-dependent energy forms that are more flexible, more convenient, and cleaner. This is a function of three major underlying trends in the "quality ladder" of different energy currencies:
    - Industrial processes and technologies are becoming ever more complex, with increasing requirements for ease of handling, storability, continuity, and flexible availability of energy supplies.
    - Requirements for convenience increase with rising levels of affluence, so that in addition to price there is an increasing "convenience premium" determining fuel choices in residential and commercial end uses.
    - Both of these trends lead to higher "form value" (quality) of the energy currencies that are at the interface between energy supply and demand, favoring flexible, clean energy forms such as electricity, gas, and ultimately hydrogen. Put succinctly: one cannot operate a computer directly with fuelwood or coal.
- *Decreasing energy intensity:* Although per capita energy needs have increased with economic development, the specific energy needs per unit of economic activity have decreased. This ratio is referred to as energy intensity.

The trends triggered by the two grand transitions of the Industrial Revolution, and how we are likely to see them extended in the future, lie at the heart of the six scenarios explored in this report. We will return to them in detail. First, however, we should recognize that, because the Industrial Revolution started in Europe and spread at different speeds to other parts of the world, there are now substantial disparities around the globe. These disparities among regions will translate into important differences in their future patterns of development. Thus the next section examines current disparities.

3.2. Disparities in Income and Energy Consumption

Levels of economic development, standards of living, and access to energy services are distributed distinctly unevenly around the world. Disparities are evident even at high levels of regional aggregation, as shown in *Figure 3.2* (based on the 11 regions

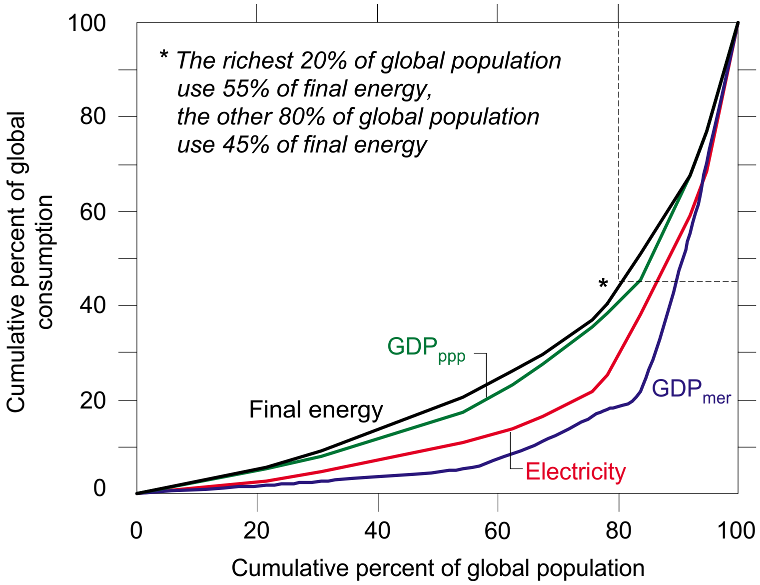


Figure 3.2: Disparities in economic activity and energy consumption in 1990. Cumulative percentage of global economic product, GDP$_{mer}$ and GDP$_{ppp}$, and consumption of final energy and electricity by percentage of cumulative global population.

used in this study), and become accentuated as we consider more disaggregated regions, individual countries, and eventually different social strata within countries.

Comparisons based on GDP show the richest 20% of the world's population producing and consuming 80% of the value of all goods and services globally. The poorest 20% dispose of only 1% of global GDP. In 1990, GDP per capita varied by a factor of 70, from US$22,800 per capita to US$330 per capita, between PAO and SAS, respectively. Disparities among individual countries and among different social strata are even more pronounced. The poorest 20% in Bangladesh, for example, have a per capita GDP of less than US$90. That is a factor of 700 lower than the US$60,000 annual income of the top 20% in Switzerland.

Such disparities are somewhat reduced when comparisons are based on GDP calculated on the basis of purchasing power parities (GDP$_{ppp}$) and not on GDP calculated at market exchange rates (GDP$_{mer}$). GDP$_{ppp}$ corrects for divergences between formal exchange rates and the relative purchasing power of different currencies (see *Box 3.1*). Nonetheless, disparities remain significant. The richest 20% consume 60% of global GDP$_{ppp}$, while the poorest 20% consume only 5%. Per capita GDP$_{ppp}$ differs by a factor of 17, for example, between SAS and NAM. The relative per capita income ranking of regions remains quite stable, however,

Box 3.1: Purchasing power parities

A nation's GDP is defined as the money equivalent of all products and services generated, sold, and bought in that nation's economy in a given year. The gross national product (GNP) is equal to the GDP *plus* the net balance of international payments to and from the country.

A major difficulty in comparing GDPs across countries is the need to translate everything into a common currency. Most often this is done using market exchange rates, with the US dollar as the common currency. Problems arise for several reasons. First, not all economies have a free market for foreign currency exchange. Second, the use of market exchange rates implicitly assumes that domestic prices are comparable with international prices. This is not the case for most developing countries, where prices for food and basic services, for example, are substantially below international levels. Third, many transactions are not accounted for in the formal economy, especially in less developed economies.

To get around some of these problems, the concept of purchasing power parities has been developed (see UNDP, 1993). A country's $\mathrm{GDP}_{\mathrm{ppp}}$ is simply its GDP in US dollars, corrected for the differences between domestic and international prices. In this report we use the notation $\mathrm{GDP}_{\mathrm{mer}}$ and $\mathrm{GDP}_{\mathrm{ppp}}$ to distinguish between calculations based on market exchange rates and those based on purchasing power parities, respectively. Where GDP appears without a subscript, it refers to $\mathrm{GDP}_{\mathrm{mer}}$.

International comparisons using $\mathrm{GDP}_{\mathrm{ppp}}$ present a picture different from those based on $\mathrm{GDP}_{\mathrm{mer}}$. For example, 1990 $\mathrm{GDP}_{\mathrm{mer}}$ per capita is higher in EEU than in CPA by about a factor of six (US$2,400 versus US$380). The ratio drops to about three using 1990 $\mathrm{GDP}_{\mathrm{ppp}}$ per capita (US$5,800 versus US$2,000). Taken together, the $\mathrm{GDP}_{\mathrm{mer}}$ of the OECD countries equals 80% of the world total. OECD $\mathrm{GDP}_{\mathrm{ppp}}$, however, is 55% of the global total. In this report, Case A's ambitious economic growth rates result in CPA's $\mathrm{GDP}_{\mathrm{ppp}}$ surpassing the current $\mathrm{GDP}_{\mathrm{ppp}}$ for NAM by 2010. In terms of $\mathrm{GDP}_{\mathrm{ppp}}$, CPA becomes the largest regional economy of the world around 2040. If progress is measured by $\mathrm{GDP}_{\mathrm{mer}}$, however, this catch-up process is shifted toward the end of the 21st century.

regardless of whether the comparison is based on per capita $\mathrm{GDP}_{\mathrm{mer}}$ or per capita $\mathrm{GDP}_{\mathrm{ppp}}$.

Disparities in energy availability mirror the economic disparities among regions. The richest 20% of the world's population use 55% of final and primary energy, while the poorest 20% use only 5%. (For a definition of final energy, see *Box 5.1*.) In 1990, per capita use of final energy varied by a factor of 18 between SAS and NAM – from 0.3 toe per capita to 5.3 toe per capita, respectively (*Figure 3.3*). Of all energy carriers, the disparities are largest for electricity. The richest 20% use 75% of all electricity, while the poorest 20% use less than 3% (see

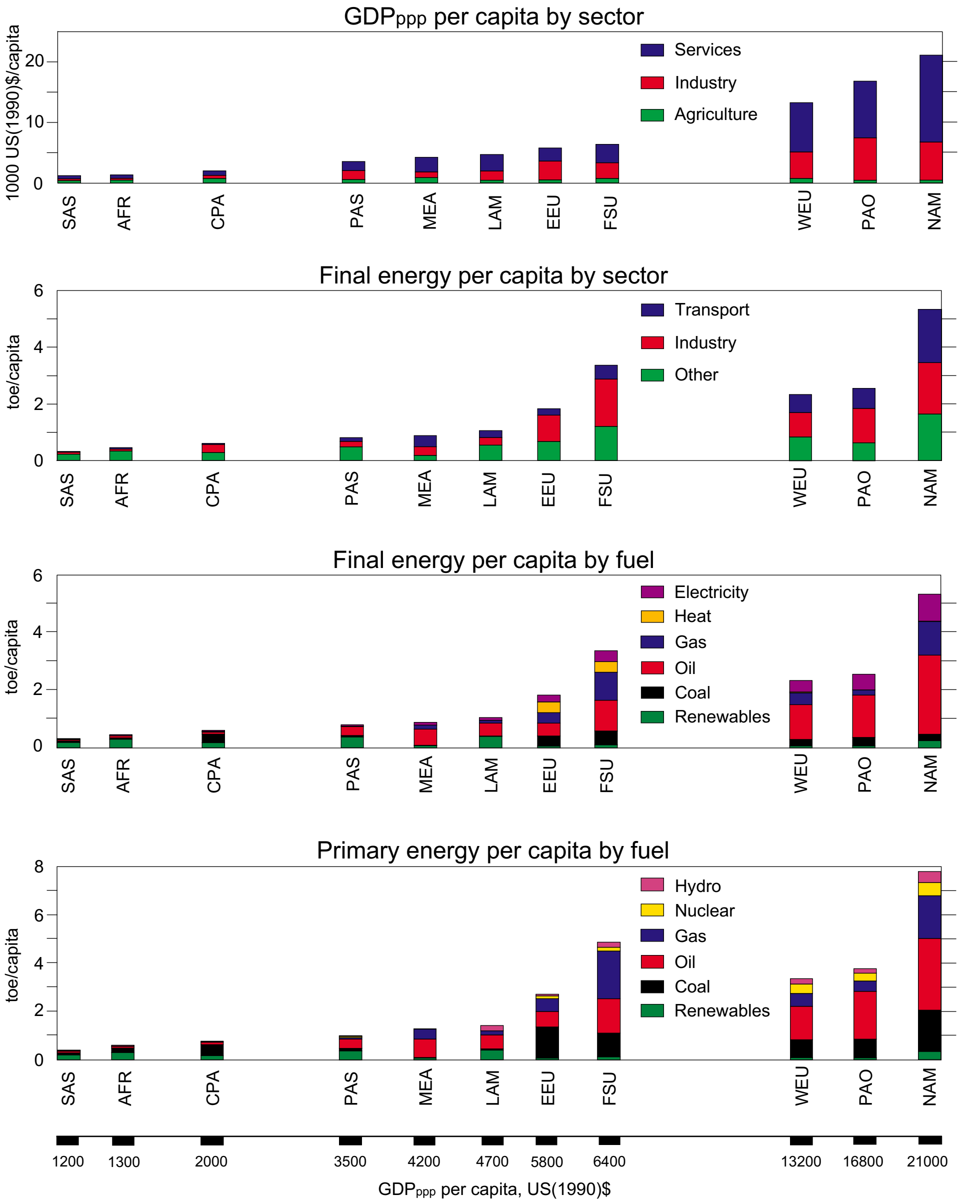


Figure 3.3: Per capita levels and structure of economic activity, GDP$_{\text{ppp}}$ per capita in US(1990)$1,000, and primary and final energy use, in toe per capita, for 11 world regions in 1990. Regions are grouped from left to right by their per capita GDP$_{\text{ppp}}$. Data sources: Hall and Rosillo-Calle, 1991; IEA, 1993, 1994; World Bank, 1993, 1994; UN, 1993b, 1993c.

Figures 3.2 and *3.3*), reflecting their much more limited access to commercial energy in general, and to electricity in particular.

These large disparities, combined with future population growth, are important drivers of future energy demand and supply. However, it would be both simplistic and misleading to expect that present disparities will disappear rapidly and that global consumption levels will approach the upper bounds of today's consumption in industrialized countries. Such rapid convergence models have been the source of serious overestimates in some past energy demand scenarios, notwithstanding the ethical appeal of global consumption levels rapidly "catching up" to those prevailing in the industrialized countries.

3.3. Economic and Energy Structures

Regional disparities in per capita GDP ($\mathrm{GDP}_{\mathrm{mer}}$ and $\mathrm{GDP}_{\mathrm{ppp}}$ alike) are correlated with differences in economic structure (*Figure 3.3*). Lower per capita GDP is associated with a high share of agriculture. Industry's share of both GDP and employment increases with increasing incomes until high levels of per capita GDP are reached. Then the share of industry begins to decline and that of services increases, illustrating the emergence of "post-industrial" or "service" economies.

A similar structural change can be seen in final energy use. At low per capita GDP, residential energy uses dominate – based largely on traditional energy carriers. With increasing incomes, the shares of industry and of commercial energy carriers, particularly liquids, increase. At high per capita GDP, final energy demand is dominated by the transportation sector and, again, the residential sector, this time based on commercial rather than noncommercial fuels. The energy portfolio is dominated by high-quality, grid-dependent energy forms like electricity, district heat, and gas, while the share of solid fuels (i.e., traditional biomass and coal) declines.

Similar structural differences can be seen in primary energy supplies. The correspondence is not perfect, however, because of differences in regional resource availability and the energy sector's ability to draw on a variety of primary energy sources to meet final energy demands.

3.4. Energy Intensities

Energy intensities, measured as energy requirements per unit of economic activity, also show great differences across regions. They can be expressed in four different ways, depending on whether the numerator includes or excludes noncommercial energy, and depending on whether the denominator is $\mathrm{GDP}_{\mathrm{mer}}$ or $\mathrm{GDP}_{\mathrm{ppp}}$. All four are shown in *Figure 3.4* for both primary and final energy use.

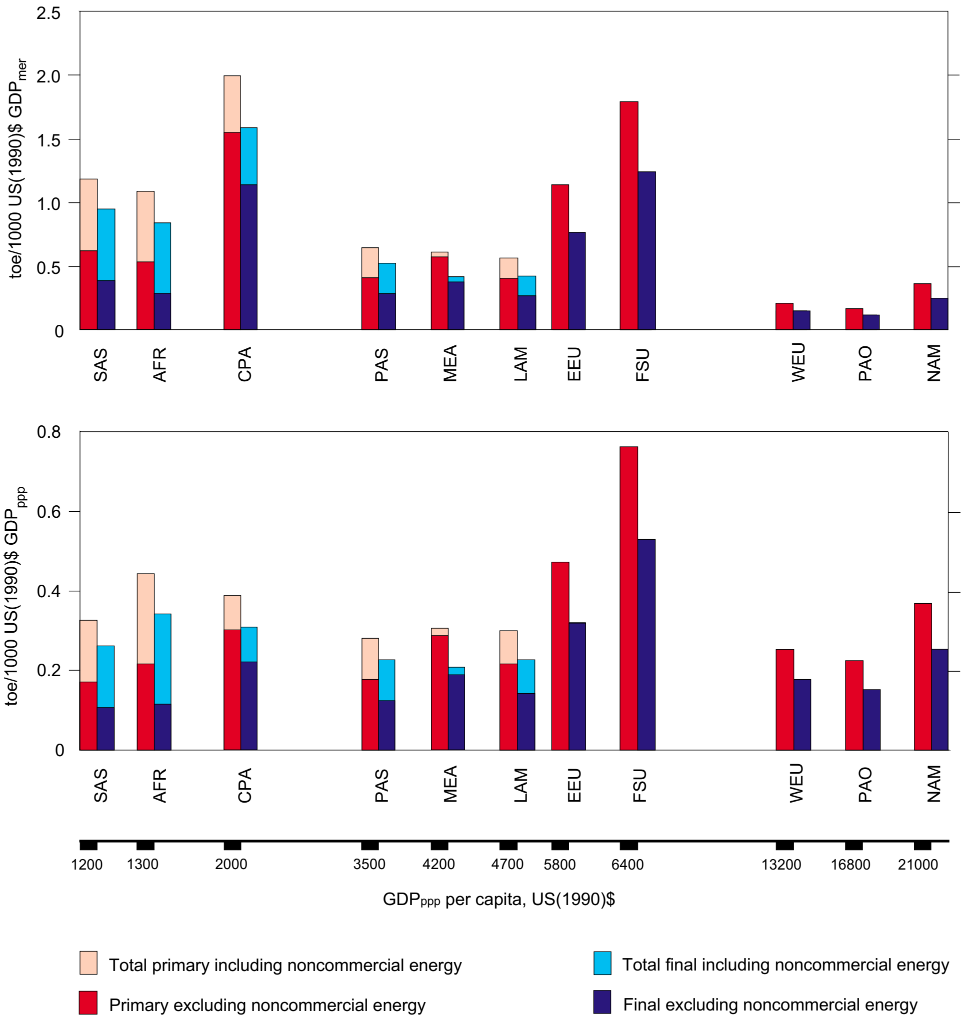


Figure 3.4: Primary and final energy intensities, including and excluding noncommercial energy, in energy per GDP_{mer} (*top*) and per GDP_{ppp} (*bottom*). Regions are grouped from left to right according to their per capita GDP_{ppp} in 1990.

The influence of different accounting conventions is apparent in *Figure 3.4*. For example, the primary energy intensities of CPA and PAO differ by a factor of 16 when GDP_{mer} is used and noncommercial energy is included. The difference decreases to a factor of 2.7 when GDP_{ppp} is used. The variations are less striking, though still significant, when comparing energy intensities including noncommercial energy with those leaving it out. For example, in the extreme cases of SAS and AFR, including traditional biomass use doubles primary energy intensity. Overall, we believe that energy intensities using $\mathrm{GDP}_{\mathrm{ppp}}$ more accurately reflect relative differences in the efficiency of energy use than do those using $\mathrm{GDP}_{\mathrm{mer}}$.

An important characteristic of *Figure 3.4* is that, with the exception of the former centrally planned regions, energy intensities are lower at higher per capita GDP. This correlation is the result, first, of more efficient energy conversion and end-use technologies that become affordable at higher income levels, and, second, of the higher quality of energy carriers made available by the energy sector in high-income economies. Consider the case of cooking: while the thermal efficiency of a traditional fuelwood cooking stove is less than 10%, an electric oven can achieve efficiencies in excess of 70%. However, the electric oven requires both the availability of capital (as it is at least five times more capital intensive than the traditional cooking stove) and high incomes (given the high price of electricity).

The disparities across regions highlighted in this section largely mirror the changes that present-day industrialized countries have witnessed during their development over the past 150 years. In particular, the trend across regions toward lower energy intensities at higher incomes shown in *Figure 3.4* is consistent with long-term historical trends within high-income countries. Energy intensities in today's developing economies are quite similar to levels that characterized many of the OECD countries when they had similarly low levels of per capita income and were developing economies themselves. This consistent trend is incorporated in all three of the cases described in the following sections.

3.5. Recent Developments: 1990 to 1998

To ease comparability with *Energy for Tomorrow's World* (WEC, 1993) and *Global Energy Perspectives to 2050 and Beyond* (IIASA–WEC, 1995), we have retained 1990 as the base year for this study. For completeness, this section summarizes actual short-term developments during the past few years, relying both on statistics through 1997 (BP, 1995, 1997; World Bank, 1995, 1997a) and on short-term forecasts through 2006.

3.5.1. Economic growth

Between 1991 and 1995, the world economy continued to expand, although at a sluggish rate of about 2% per year. GWP grew by 2.5% in 1995 and was estimated to grow by almost 2.9% in 1996. The World Bank projects an even more robust average growth rate of 3.4% from 1997 to 2006, as the rapidly growing economies of large developing and "transition" countries tend to push GWP upward (World Bank, 1997a, 1997b).

Regional experience has been varied (see Chapter 7). Growth in the OECD regions (NAM, WEU, and PAO) between 1991 and 1995 averaged 1.8% per year, with a tendency toward higher growth in more recent years: 2.0% for 1995, an estimated 2.3% for 1996, and a projected 2.7% for 1997 through 2006 (OECD, 1996; World Bank, 1997a). CPA's GDP grew at about 10% per year, while GDP in the FSU region declined by nearly 10% per year between 1991 and 1995 (World Bank, 1997a). Indeed, since the early 1990s the reforming economies have suffered an economic depression unprecedented in recent history, which has been mirrored by drastic reductions in energy demand (see Bashmakov, 1990; Commission for the Energy Strategy of Russia, 1995; Dienes *et al.*, 1994; EIA, 1994; Government of the Russian Federation, 1995). In the developing regions, average annual GDP growth has been close to 5%. There is substantial variation among countries; Asia has seen the most impressive growth, while growth in Africa and the Middle East has been sluggish.

Although barriers to economic cooperation still exist, geopolitical tensions have diminished somewhat since 1990. The 1994 agreement on trade liberalization and the formation of the World Trade Organization (GATT, 1994) have advanced prospects for global economic integration, and world trade is expected to be the "engine of growth" (World Bank, 1995) of the next decade. At the regional level, economic integration has also advanced, as exemplified by the North American Free Trade Agreement (NAFTA) and the expansion of the European Union (EU). New member countries are expected to join the EU in coming years, and a common European currency will be introduced in early 1999. There has also been a significant increase in the number of international environmental agreements, most recently the Kyoto Protocol to the United Nations Framework Convention on Climate Change (see WEC, 1995a, 1995b; UN/FCCC, 1997; Bolin, 1998).

3.5.2. Energy developments

Global primary energy demand has grown more slowly than GDP. Primary energy growth averaged slightly above 1% per year between 1990 and 1995, about half the rate of growth of global GDP. Thus, global energy intensities continue to improve, except in some transitional economies.

Nearly all the additional primary energy demand growth has been for commercial energy forms, though there was variation across energy sources. Petroleum continues to be the world's primary energy source, followed by coal and natural gas. Global demand for coal stabilized between 1990 and 1995. Gas, renewables, and nuclear energy, on the other hand, expanded their shares between 1991 and 1996 (BP, 1997; EIA, 1998a, 1998b).

Regional differences have been enormous. In the OECD region, primary energy demand grew at nearly the same rate as the economy; in other words, energy intensity improvements came close to a standstill. In reforming economies, primary energy demand fell by approximately one-quarter. But the even greater drop in economic output meant that energy intensities increased significantly. Since 1990, CPA's total primary energy use increased by about 4% per year and close to 5% per year for commercial energy. Compared with a GDP growth rate of 10% per year, this translates into energy intensity improvements of 6% per year (5% per year for commercial energy). In developing countries outside CPA, total primary energy growth was some 3% per year (over 4% per year for commercial energy), compared with a GDP growth rate of 4% per year. Thus, aggregate energy intensity declined by about 1% per year, whereas commercial energy use grew at roughly the same rate as the economy (see also Chapter 7). The overall pattern is therefore one of decreasing energy intensities where economic growth is strong, stagnating energy intensities where growth is sluggish, and increasing energy intensities where growth is negative. This matches the patterns discussed in both this section and the next and is incorporated in all three cases in this study.

In the mid-1990s many OECD countries and to a lesser extent LAM began the process of deregulating their electricity markets to introduce greater competition and reduce costs. This process involves changes in the structure, ownership, and regulation of the power sector. For example, production, transmission, and local distribution have been unbundled into separate accounting units, and third parties have been granted access to transportation and distribution grids (OECD, 1996). Privatization of large, state-owned energy companies is a key element of deregulation in several countries. Although it is too soon to know precisely what the impacts of this will be on future energy consumption patterns, restructuring may well lead to diversification of energy supplies. Restructuring has also raised environmental concerns in some countries, as increased use of comparatively inexpensive coal could result in greater emissions of CO_2, sulfur oxides (SO_x), and nitrogen oxides (NO_x).

Taken together, recent short-term developments in the economy and energy most closely resemble the middle-course Case B.

Chapter 4

Determinants of Future Energy Systems

The historical developments and current disparities summarized in Chapter 3 provide the starting point for all three cases described in this book. In this chapter we summarize the key driving forces that influence how the three cases evolve from their common starting point. We divide these driving forces into six categories – population growth, economic growth, energy intensity improvements, technological change, the resource base, and environment.

4.1. Population Growth

In all three sets of scenarios – Cases A, B, and C – a common central (i.e., medium) projection of the world's population is assumed. We chose to use the same pattern and growth of population in all cases so that the differences that emerge among our cases are more easily connected to differences in their energy systems and their driving forces. Here, we describe the central population projection we chose and how it compares with available alternatives.

We used the single projection published by the World Bank in 1992 (Bos *et al*., 1992), which is the same as that used in *Global Energy Perspectives to 2050 and Beyond* (IIASA–WEC, 1995). First we compare it with alternative projections and recent developments. We then assess the implications of the uncertainty in the World Bank and other population projections for the six scenarios and overall study results presented later.

The World Bank projection published in 1992 is consistent with other central projections developed at the time. Most important for the choice made in this study is the fact that the World Bank has been the only source that provides long-term, country-by-country projections. These we judged essential for this study, not least because of the high degree of regional detail required for analyzing the 11 world regions adopted in this study. In more recent studies, the central projections for the year 2100 have declined somewhat but are essentially the same as the World Bank projection for the next 50 years. These more recent studies include the United Nations (UN, 1998), the US Census Bureau (McDevitt, 1996), and the International Institute for Applied Systems Analysis (IIASA; Lutz, 1994, 1996). This is also consistent with the World Bank's own subsequent updates (Bos and Vu, 1994) – now no longer published.

Overall, the good news in the 1992 World Bank and other global projections is that population growth is slowing down. The next doubling of the world's population will take longer than the last one. In absolute numbers, of course, the next doubling will be the biggest ever. In the 1992 World Bank projection, global population doubles from 5.3 billion people in 1990 to 10.5 billion in 2060, a doubling time of 70 years. For comparison, the last doubling took approximately 40 years. Beyond 2050, population growth slows significantly and global population stabilizes at around 12 billion. In 2100, the value is 11.7 billion. Virtually all of this population growth is in the South (*Figure 4.1*).

The inevitable demographic momentum implies that uncertainties in demographic projections translate into noticeable differences in global population numbers only in the very long term (i.e., after 2050). For instance, the more recent assessments by the UN (1998) project global population by 2050 to increase to 9.4 billion and those by IIASA to 9.9 billion people (Lutz, 1996), compared with the 10 billion people of the 1992 World Bank projection used in this study. After 2050, the more recent demographic projections begin to diverge from the older ones. For instance, the latest UN (1998) medium-low and medium-high projections indicate a range of between 7.2 and 14.6 billion by 2100, with the medium scenario at 10.4 billion. As is the case with most projections, the UN does not attach probabilities to its population variants. The one study that does attach probabilities to alternative projections is IIASA's 1996 revision of estimates it originally published in 1994 (Lutz *et al.*, 1997). For the 1996 revision IIASA canvassed a group of demographic experts to assign subjective probabilities to possible future trends in fertility, mortality, and immigration in different regions of the world. These were then combined, taking into account possible correlations among the three factors, to yield probabilistic projections at both the regional and global levels. The 1992 World Bank projection used in this study corresponds approximately to IIASA's 70th percentile for 2100 (see *Figure 4.2*). That is, based on the judgment of the demographic experts it assembled, IIASA estimates that there is a 70% chance that the world's population growth will be below the 1992 World Bank projections used in this study. Conversely, there is a 30% chance that actual population growth will be higher than the 1992 World Bank projection.

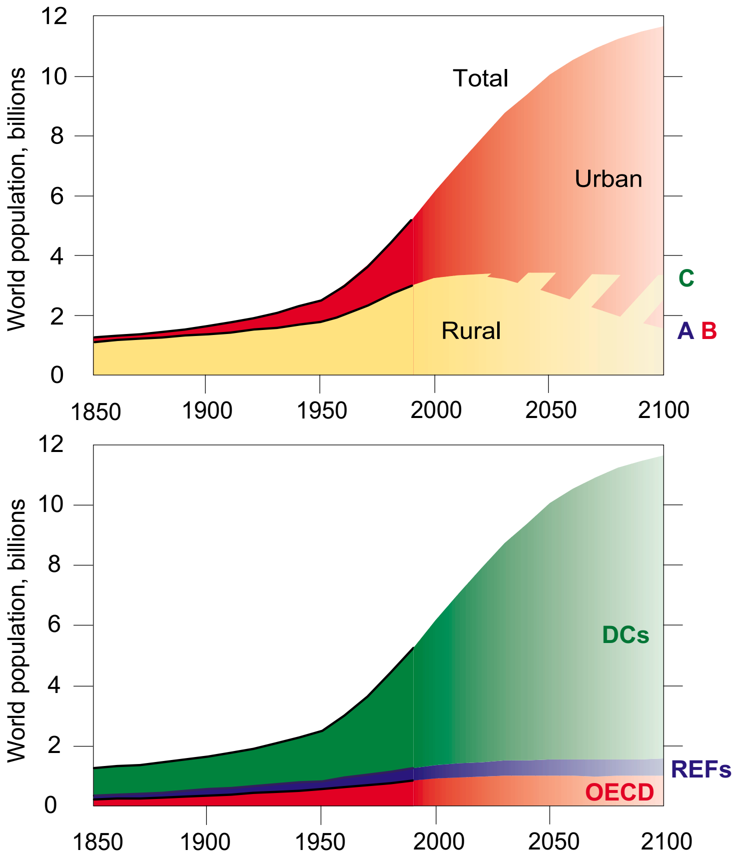


Figure 4.1: World population showing historical development from 1850 to 1990 and World Bank projection to 2100 (Bos *et al.*, 1992), (*top*) rural–urban and (*bottom*) by macroregion, in billion people. Urbanization trends are based on UN (1994) and Berry (1990).

One reason the 1992 World Bank projection used in this study is slightly higher than IIASA's 1996 and UN's 1998 central projections is that fertility has declined faster during the 1990s than originally anticipated (Cleland, 1996). More recent projections incorporate this faster fertility decline in their calculations and thus project lower future populations than do earlier studies. Thus IIASA's own projections dropped from a 1994 central estimate of 12.6 billion people in 2100 to a revised central estimate of 10.4 billion. The 1998 UN long-range population projection of 10.4 billion by 2100 is also lower than their 1992 estimate of 11.2 billion.

Despite these various adjustments and updates among demographers, we have retained the 1992 World Bank projections for four reasons. First, we have no objection to being a bit conservative. If actual population growth comes in slightly below what is assumed in this study, so much the better. Lower than anticipated population growth would result in somewhat lower energy growth. That lower population growth globally results in lower energy growth is not as uncontentious a statement as it might seem at first blush. Among the study's reviewers are those who argue that too rapid population growth may well slow economic growth. The corollary is that slower population growth could speed economic growth and thus growth in energy demand. We agree that a reduction in population growth does not automatically mean a *proportional* reduction in energy growth, but it does mean some reduction in energy demand. (Conversely, higher population growth would not necessarily lead to a proportional growth in energy demand, either.)

A second reason we retained the original 1992 World Bank population projections is that several of the study's regional review groups considered these too *low* and several other considered them too *high* for their regions, the latter being consistent with the demographic updates described above. The regions that thought the projections are too low included AFR, MEA, and NAM, and regions that thought them too high included CPA, EEU, and SAS. The regional demographic patterns and the implications of regional reviews are discussed in greater detail in Chapter 7. In the face of these competing forces tugging in opposite directions, we initially considered developing variations of the study's six scenarios incorporating alternative high and low population projections. But this quickly led to the third reason to retain the 1992 World Bank population projection.

The third reason is that varying population blurs the study's conclusions about *energy*. Moreover, if population is varied independently of energy developments, adding high and low population variants turns six scenarios into 18. If the basic conclusions of the study are unlikely to change (a point we return to below), the 12 new scenarios would add little new information, only many more pages of text and likely confusion. On the other hand, if population variations are *not* independent of energy developments (e.g., if Case C is believed to be more consistent with low population variants than Case B), then the addition of population variants overlays the energy picture with demographic debates. The relationship between population and economic growth continues to be controversial (NRC, 1986; MacKellar *et al.*, 1998; Gaffin, 1998). Perspectives range between those who argue that population growth hinders economic development ("more mouths to feed") and those who consider population growth an important driver of economic growth ("more hands to work").

The fourth and final reason we retained the 1992 World Bank population projection is that sensitivity analyses indicate little reason to expect that the study's major conclusions would change significantly if population were varied within a reasonable range of uncertainty as indicated by IIASA's 1996 probabilistic projections. (At present no one can really venture into the full implications of

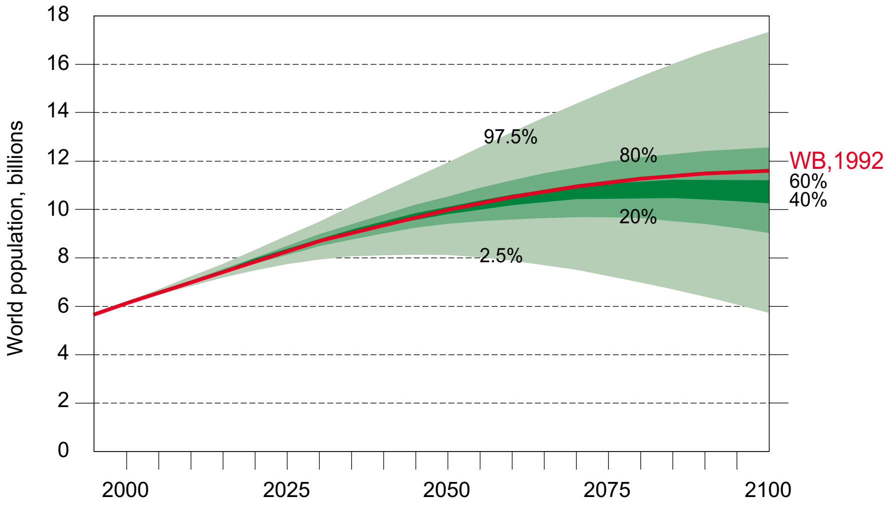


Figure 4.2: Probabilistic population projections for the world compared with the 1992 World Bank projection used in this study (shown in red). Probabilities of alternative population projections are given in percent. Source: adapted from Lutz, 1996.

extreme demographic outcomes ranging between collapse, for example, a decrease from 10 to 5 billion between 2050 and 2100, and a veritable explosion, such as an increase to 20 billion by 2100.[1]) Indeed the range of uncertainty is relatively narrow. As shown in *Figure 4.2*, the range between the 80th percentile and 20th percentile in 2100 runs only from 12.6 to 9.0 billion people, which is less than 8% higher and 23% lower than the 1992 World Bank projection used here. Sensitivity analyses performed with coupled demographic and energy models indicate that changing the population assumptions in the scenarios, in either direction, would lead to less than proportional changes in energy demand. For example, if we were to use IIASA's 80th percentile population projection of 12.6 billion people in 2100 in Case B, energy demand would likely be no more than 5% higher – that is, it would remain within the inevitable uncertainty range of any individual scenario, and more important it would be well below the range spanned by alternative developments, such as those described in Case A. Similarly, adopting IIASA's 20th percentile population projection of 9 billion by 2100 would result in a decrease of energy demand on the order of 10% in Case B. The weak inverse relationship between population growth and per capita economic growth incorporated in our scenarios would lead to higher per capita incomes (and energy demand); faster per

---

[1] Population was varied in the 1992 IPCC emissions scenarios across the full range of projections as a kind of sensitivity analysis, see Pepper *et al.*, 1992.

capita economic growth would in turn lead to quicker improvements in energy intensities in a less populated but more affluent world (which in turn would tend to lower energy demand). Thus, little additional insight is provided beyond that from Case C, which focuses on international development, equity, and environmental protection and thus on accelerated energy efficiency improvements and resulting low energy demand.

The above illustrations of increases and decreases in energy demand that would result from a reasonable range of alternative demographic projections are not enough to alter the basic patterns of change in the six scenarios, only to accelerate them slightly. In particular, the implied changes are not enough to open significantly different perspectives from those spanned between Case C (low demand) and Case A (high demand). They also would not cause any of the scenarios to encounter new and different resource or capital constraints. We thus believe that the results that are robust vis à vis the uncertainty range spanned by our three cases and six scenarios remain equally so in the face of demographic scenario variations.

Based therefore on the single 1992 World Bank population projection, the six scenarios examined in this study reflect only a weak relationship between population growth and economic growth. Two hypotheses are incorporated. First, the takeoff period of maximum growth of GDP happens sooner in those developing countries already more advanced in their demographic transition. Thus, the economic takeoff occurs sooner in China, where recent GDP growth rates have been approximately 10% per year and fertility rates are already low. In regions like SAS, where modest declines in population growth rates are just beginning and rapid declines come only well into the next century, the economic takeoff occurs later. Second, for industrialized countries, economic growth rates are lower in regions with possible declining populations, such as Japan after 2050, than in regions with stable or slightly increasing populations.

For future energy development, the two most important features of world population growth are consistent across all global projections available in the literature: World Bank, IIASA, UN, and US Census Bureau. The first is urbanization; the second is the concentration of future growth in the developing countries.

Increasing urbanization (*Figure 4.1,* top) is a pervasive trend in all countries. More than 80% of the population of industrialized countries live in urban environments, and many developing countries show similar high urbanization rates. According to the UN, 2.2 of 5.3 billion people lived in urban agglomerations in 1990. Over the next 35 years the urban population is projected to increase to 5.2 billion, an amount equal to the total global population in 1990. That increase of 3 billion accounts for nearly all the projected population growth of 3.2 billion over the next 35 years (UN, 1994). Thus, almost all additional global population growth will be urban. According to the UN (1994), 60% of the world's population will live in urban areas by 2025, and, if historical tendencies continue, three-quarters of the global population (approximately 8 billion people) will live in urban agglomerations by 2050. An increasing fraction will live in "megacities" with over 10 million inhabitants. It is estimated that shortly after the year 2000, eight cities will have more than 15 million inhabitants, only two of which, Tokyo and New York, are in highly industrialized countries. The remaining six (Beijing, Bombay, Calcutta, Mexico City, São Paulo, and Shanghai) are in the now developing world.

Providing adequate and clean energy services for a world whose population lives predominantly in urban areas will be a daunting task. Per capita energy use in urban areas is much higher than national averages, largely as a result of higher urban incomes (Sathaye and Meyers, 1990). Energy transport and conversion infrastructures that match urban energy demand densities will need to be put in place, and energy efficiencies will need to improve to at least partly offset demand growth and urban environmental impacts, especially in developing countries. Case C, with its greater emphasis on decentralized, small-scale, renewable sources of energy, provides a basis for slower rates of urbanization and for satisfying rural energy requirements at lower costs than in Cases A and B, but the broad trend is in the same direction in all cases.

The second critical feature of global population growth is by now well known and needs little elaboration – future growth will be concentrated in the developing countries (see *Figure 4.1*). By 2100, the population of the USA, Canada, and the whole of Europe combined drops to less than 10% of the world total, as indeed suggested by all central scenarios of the World Bank, IIASA, and the UN. One possible consequence is a major shift in the world's geopolitical balance in favor of the developing world, which may strengthen its ability to obtain and retain both internationally traded energy forms and access to technology.

4.2. Economic Growth

Economic development and growth are fundamental prerequisites for achieving an increase in living standards with the kind of vigorous global population growth described in the previous section. Although the definitive (and quantitative) long-term history of world economic output has yet to be written, it is fair to say that current disparities between North and South and between East and West are rooted largely in differential growth rates of economic output over extended historical periods (see *Table 4.1*). Small differences in these growth rates, when compounded over a generation or more, have much greater consequences for standards of living than even the most dramatic short-term business fluctuations.

Both classical and modern economic growth theory offer some insights into the mechanisms of successful economic development and the remaining disparities

Table 4.1: Economic growth rates, historical and 1990 to 2050, in percent per year.

	Historical			Case					
	GDP_{mer}		GDP_{ppp}						
	Since	Since	since	1990 to 2020			2020 to 2050		
Region	1850	1950	1950	A	B	C	A	B	C
NAM	3.5	3.3	2.1	2.3	2.0	1.7	1.6	1.3	1.1
WEU	2.4	3.7	2.2	2.2	1.9	1.7	1.7	1.3	1.1
PAO	3.9	6.2	3.6	1.9	1.5	1.4	1.3	0.9	0.8
EEU	2.1	3.9	2.4	2.3	0.9	1.3	4.6	3.6	3.2
FSU	3.5	5.2	3.5	1.2	0.7	1.1	5.4	3.8	3.3
CPA	2.9	6.1	4.3	7.2	5.0	6.7	4.4	4.0	4.0
SAS	2.0	4.5	3.1	3.9	3.5	3.7	4.6	3.5	4.3
PAS	n.a.	9.8	6.8	5.7	4.4	5.3	3.3	3.1	3.1
MEA	n.a.	4.6	3.1	3.6	3.3	3.3	3.9	3.0	3.0
AFR	n.a.	2.7	2.0	3.3	3.0	3.1	4.7	3.5	3.9
LAM	3.7	4.2	2.9	3.1	3.0	3.1	3.2	2.8	2.8
World	n.a	4.0	2.8	2.7	2.2	2.2	2.6	2.0	2.1

n.a. = not available.
Sources for historical data: Maddison, 1989; UN, 1993a, 1993c.

among countries.[2] In addition to the traditional "tangible" factors driving economic development, such as technology, capital, natural resources, and trade possibilities, "intangible" factors such as the quality of human capital and institutions, limited income disparities, and social cohesion increasingly explain the historically uneven paths of economic development. The bottom line is that growth possibilities do not fall like "manna from heaven" but are largely determined by endogenous factors including knowledge (research, development, and demonstration, RD&D), skilled human capital (education), and a favorable social and institutional climate (e.g., social protection of the work force and a fair distribution of productivity gains).

Combining the insights of classical and modern economic growth theory, the fundamental forces driving developing economies to catch up to developed economies are differences in productivity and in knowledge and technologies applied in production. Because it is generally easier to catch up to the productivity frontier than to push it further, developing economies have the potential, as they close the productivity and technology gap, for much higher growth rates than leading economies. Realizing this potential requires functioning markets and at least partially favorable "intangible" factors, but there is no compelling *a priori* reason to rule out future successful economic development even in regions where recent growth prospects have been far from auspicious, such as sub-Saharan Africa.

---

[2] See, e.g., Aghion and Howitt, 1998; Barro, 1997; Grossman and Helpman, 1991; Maddison, 1995.

The historical successes of much of Western Europe, Japan, and more recently the "Asian Tigers" all point in this direction. The potential for developing economies to catch up to economic leaders does not mean that success can be taken for granted, nor should one be surprised that overall progress is overlaid with short-term business cycle fluctuations and even financial crises. Rapid growth can aggravate small imperfections that can ultimately lead to crisis. However, the key lesson is the importance of maintaining a long-term perspective when facing short-term downturns and fluctuations: the developing world *can* catch up, although the gap to the most developed countries will not be entirely closed by 2100.

Successful cases of industrialization and catch-up all appear to be characterized by a similar dynamic pattern. After a particular development threshold is passed, economic growth accelerates, passes through a maximum, and then decreases once the industrial and infrastructure base of an economy is firmly established. Historical data support Rostow's (1980) thesis that "the poor get richer and the rich slow down." This conceptual model has been incorporated into the time path of economic development underlying the three cases (*Figure 4.3*).

Many alternatives have been proposed for the conditions that trigger the "take-off" into economic development. Recent research (Lucas, 1988; Romer, 1986; UN, 1997; World Bank, 1997b) places less emphasis on physical endowments, such as land, minerals, and energy. More emphasis is given both to intangible factors – such as appropriate institutional arrangements, the market orientation of an economy, trade, and education – and to traditional explanatory variables – such as technology availability and transfer, savings rates, and other factors influencing labor productivity. These "intangible" social and institutional factors are, however, difficult to quantify for a scenario exercise and for the most part must be dealt with qualitatively. They are assumed to be generally favorable in Cases A and C, and somewhat less so in Case B.

With these cautions in mind, let us turn to the future economic growth patterns reflected in the three cases of this study. Common to all three are the following features:

- Within the time horizon of the scenarios, all countries and regions manage to successfully take off into a period of industrialization and accelerating economic development.

- In each case, GDP per capita follows the historical pattern of an initial accelerating growth, a peak, and then an eventual decline once the economy's industrial base becomes established. Growth rates for high-income economies (OECD) decline gradually in all three cases. Because of already high income levels, future OECD growth rates are below historical rates (see *Table 4.1*). Long-term growth rates of 2% per year or lower appear modest only at first

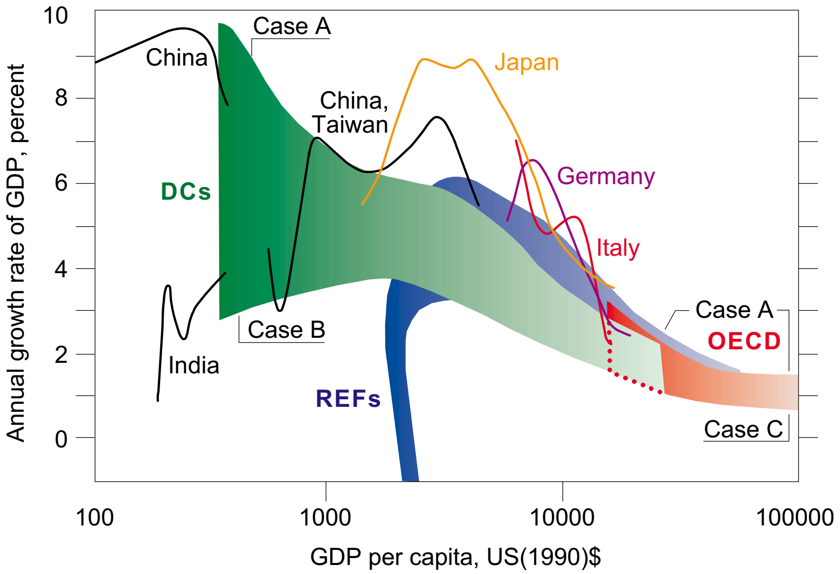


Figure 4.3: Economic growth rates, GDP in percent per year, versus degree of economic development, GDP per capita in US(1990)$, illustrating “takeoff” into industrialization, peak, and declining economic growth rates of high-income economies. Historical data for selected countries (as a 10-year moving average) and range of economic growth rates assumed in the three cases are indicated for the three macroregions: DCs, REFs, and OECD countries.

glance. They have to be contrasted with resulting per capita income levels. For example, even in the conservative Case B, per capita income in PAO reaches US$50,000 by the middle of the 21st century and US$75,000 by the century’s end.

- Where there are currently no signs of an economic takeoff, as is the case in AFR where GDP per capita is stagnating, peak economic growth is assumed to correspond to the period of maximum demographic transition (i.e., maximum decline in population growth rates).
- Short-term economic growth rates reflect data from 1991 to 1997, plus the latest World Bank (1997a) forecasts to 2006. For the economies in transition, particularly FSU, this leads to a pronounced decline during the early 1990s, as was anticipated in this study’s scenarios when they were originally formulated five years ago.

Beyond these basic commonalities, the three sets of scenarios – Cases A, B, and C – diverge in terms of economic growth patterns.

In the three Case A scenarios, the timing and speed of economic restructuring and development follow the pattern of the most successful historical examples of industrialization. This is a future characterized by free trade and favorable geopolitics. GWP increases by an average of 2.6% per year to 2050 and by 2.2% per year thereafter. The result is a fivefold expansion by 2050 and a 15-fold expansion by 2100. By 2050, average GWP per capita is US$10,000, and by 2100 it exceeds US$25,000 per capita. Average family incomes are over US$30,000 by 2050 and around US$70,000 by the end of the 21st century, based on a decline in average family size to 3.2 persons in 2050 and 2.7 persons by 2100, as is characteristic of central population projections (MacKellar *et al.*, 1995). Thus, by any standards, Case A represents a wealthy world in which the current distinction between "developed" and "developing" countries will no longer be appropriate.

The single Case B scenario also reflects significant economic expansion but incorporates more cautious expectations about geopolitics and international trade. This is a more fragmented world than in Case A, resulting in more heterogeneous patterns of economic development. For example, economic development in CPA is rapid and impressive, while that in AFR and SAS remains painfully slow. GWP again expands significantly, to US$75 trillion in 2050 and US$200 trillion in 2100. But the pace is slower than in Case A (2.1% per year), and regional disparities are larger. Through 2020 the pace of economic growth (2.2% per year) is also slower than in the original Case B of *Energy for Tomorrow's World* (WEC, 1993). This reflects recent setbacks and slow economic restructuring in EEU, FSU, and many developing countries.

The two Case C scenarios contain strong normative policy elements that distinguish them from Cases A and B. They reflect aggressive efforts to advance international economic equity and environmental protection. They include massive direct resource transfers from North to South and stringent environmental taxes, or other levies and grants, that are paid principally by OECD countries and transferred to the developing world. Such transfers constitute a positive-sum game that fuels economic growth in the developing countries and leads to GWP which exceeds that in Case B but falls short of that in Case A. GWP in Case C reaches US$75 trillion in 2050 (as in Case B) and US$220 trillion in 2100 (compared with US$200 trillion in Case B). A summary of the three cases is given in *Figure 4.4*.

It should be emphasized that in none of these cases can economic developments be taken for granted. All assume, to various degrees, numerous domestic and international policies that promote the free exchange of goods and technology, a favorable investment climate, and high levels of education and social protection for the work force. These are the necessary foundation for the formidable productivity increases of labor and capital needed to realize the high levels of economic growth reflected in all three cases. There is a risk that the energy sector could become a

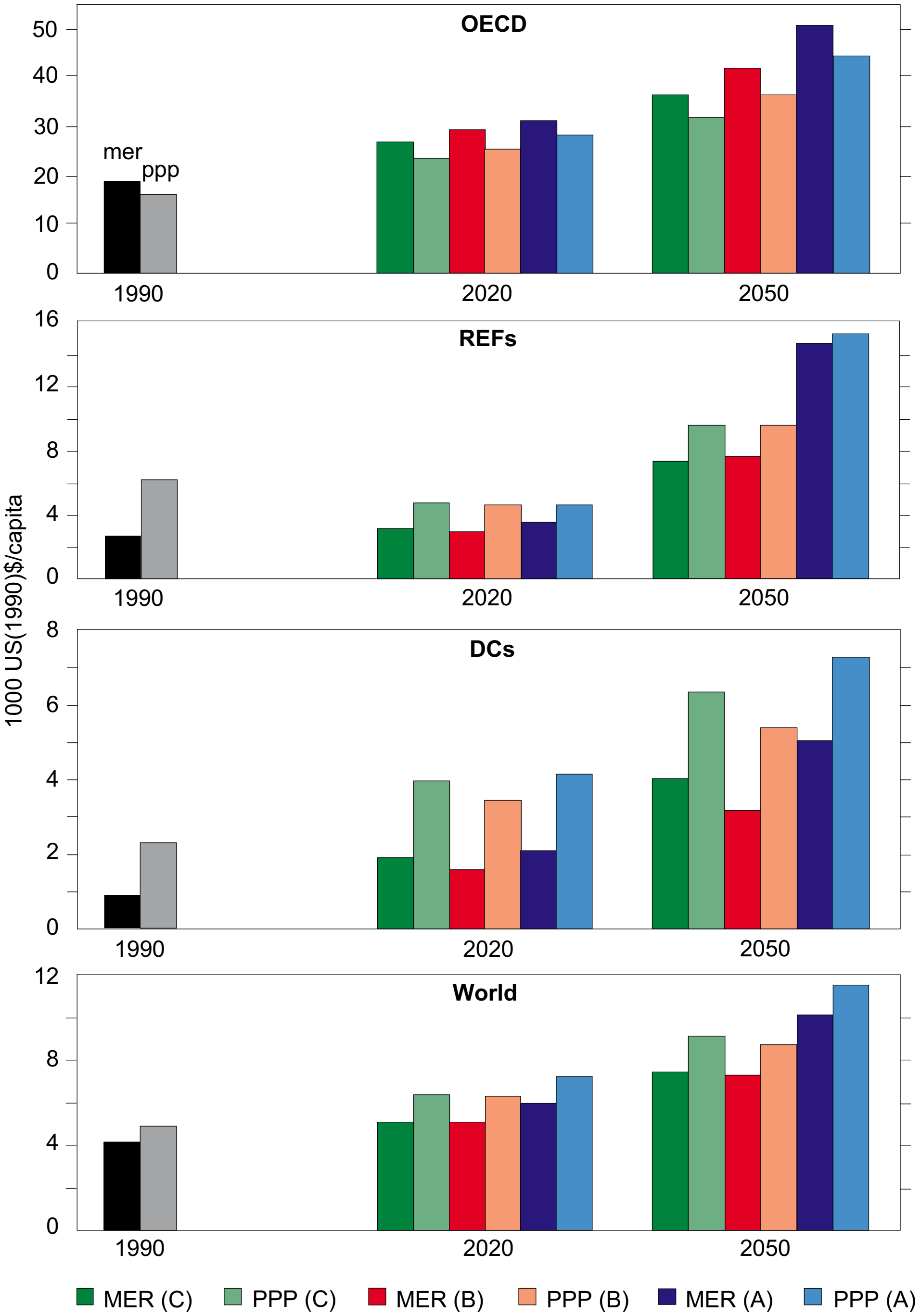


Figure 4.4: GDP per capita, in US(1990)$1,000, in 1990 and for the three cases in 2020 and 2050, in $\mathrm{GDP}_{\mathrm{mer}}$ and $\mathrm{GDP}_{\mathrm{ppp}}$.

bottleneck. It will have to compete for much-needed investment funds in a period of increasing competition where substantial funds are also needed for the health, communication, and transport infrastructures that rapidly growing economies require, for the industrial investments expanding economies need, and for the needs of rapidly growing urban areas and "megacities." The energy sector will also face greater competition for the policy attention it has traditionally enjoyed but will now have to share with a multitude of economic and development concerns. Without appropriate RD&D and investment efforts in the short to medium term, the energy sector also risks lagging behind overall productivity growth and becoming a possible long-term bottleneck for successful economic and social development.

4.3. Energy Intensity Improvements

Chapter 3 describes regional differences in energy intensities and briefly mentions the historical development in currently industrialized countries of decreasing aggregate energy intensities over time. The causes of those decreases are many and complex. They include, first, technological improvements in individual energy end-use and conversion components – for example, a more efficient stove or a more efficient power plant. They also include structural shifts in energy systems, such as a shift from coal-fired electricity generation to gas-fired combined cycle plants. They include interfuel substitution at the level of energy end use, like the replacement of fuelwood with electricity or LPG (liquefied petroleum gas). They include economic shifts from more to less energy-intensive activities. They include changing patterns of energy end uses and, ultimately, changing lifestyles.

Not every change in every one of these categories represents a decrease in energy intensity. But taken together, the overall trends are persistent and pervasive. They are incorporated into all three cases presented in this report. In this section, we present the historical evolution of energy intensities that underlie all three cases and the future development of these trends for each case individually. We do not attempt a detailed dissection of all contributing factors to improvements in energy intensities. In the next section, we discuss technological change in general and how it is incorporated into the scenarios.

In all scenarios, economic development outpaces the increase in energy use, leading to substantial reductions in energy intensities (see *Box 4.1*). As individual technologies progress, as inefficient technologies are retired in favor of more efficient ones, and as the structure of the energy system and patterns of energy services change, the amount of primary energy needed per unit of GDP – the energy intensity – decreases. In some developing regions, the intensity of commercial energy can increase initially as traditional and less efficient energy forms are replaced by commercial energy, but the intensity of total energy decreases in these cases as

Box 4.1: Energy intensity improvements in Cases A, B, and C

Energy intensity improves in all three cases as a result of economic development and improved technology. Improvement rates in Cases A and B are primarily a function of economic growth. The higher the per capita GDP growth, the higher the energy intensity improvement rate. Case C goes further to incorporate additional vigorous efficiency improvements through demand-side management and economic instruments, including substantial increases in energy prices and taxes. This is not to say that such measures might not turn out to be necessary in the other two cases. Energy intensity improvement rates for all three cases are summarized in *Table 4.2*.

Table 4.2: Three scenarios of energy intensity improvements, primary energy per $\mathrm{GDP}_{\mathrm{mer}}$, in percent per year.

	Case		
	A	B	C
	1990 to 2050	1990 to 2050	1990 to 2050
OECD	–1.1	–1.1	–1.9
REFs	–2.0	–1.7	–2.2
DCs	–1.6	–1.2	–1.9
World	–1.0	–0.8	–1.4

In comparing our energy intensity improvement rates with those of other studies and earlier WEC cases, important definitional and measurement issues have to be kept in mind. These measurement issues are illustrated for Case B for three of our 11 world regions – NAM, CPA, and SAS – giving energy intensity improvement rates (percent per year) to 2020 for total primary energy (TPE) and commercial primary energy (CPE) for $\mathrm{GDP}_{\mathrm{mer}}$ and $\mathrm{GDP}_{\mathrm{ppp}}$, respectively. For OECD regions, differences are insignificant.

Table 4.3: Energy intensity improvements, 1990 to 2020 (Case B), for three regions, in percent per year.

Region	$\mathrm{TPE/GDP}_{\mathrm{mer}}$	$\mathrm{TPE/GDP}_{\mathrm{ppp}}$	$\mathrm{CPE/GDP}_{\mathrm{mer}}$	$\mathrm{CPE/GDP}_{\mathrm{ppp}}$
NAM	–1.2	–1.3	–1.2	–1.3
CPA	–2.2	–0.7	–1.6	–0.1
SAS	–1.0	–0.3	0.3	1.0

The dynamics of energy intensity improvements change drastically for developing regions as exemplified by CPA and SAS. (The generally higher energy intensity improvements for CPA are the result of the much higher short-term economic growth rates for CPA; higher GDP growth leading to faster turnover of capital stock yields faster energy intensity improvements in the scenarios.) Thus considering the evolution of the total primary energy use per $\mathrm{GDP}_{\mathrm{mer}}$ yields a challenging pace of energy intensity improvements. Conversely, the intensity of commercial primary energy use per unit of $\mathrm{GDP}_{\mathrm{ppp}}$ remains roughly at 1990 levels (i.e., commercial energy consumption in Case B is projected to increase at the same rate as the $\mathrm{GDP}_{\mathrm{ppp}}$ for CPA).

well. With all other factors being equal, the faster the economic growth, the higher the turnover of capital and the greater the energy intensity improvements.

These long-term developments are reflected in the scenarios and are consistent with historical experience across a range of alternative development paths observed in different countries. *Figure 4.5* illustrates the range of historical energy intensity improvements for four representative countries and FSU. Energy intensities are measured both in terms of total energy divided by GDP and as commercial energy divided by GDP. *Commercial* energy intensities increase during the early phases of industrialization as traditional and less efficient energy forms are replaced by commercial energy. When this process is completed, commercial energy intensity peaks and proceeds to decline. This phenomenon is sometimes called the "hill of energy intensity." Reddy and Goldemberg (1990) and many others have observed that the successive peaks in the procession of countries achieving this transition are ever lower, indicating a possible catch-up effect and promising further energy intensity reductions in developing countries that have still to reach the peak. In the USA, for example, the peak of commercial energy intensity occurred during the 1910s and was higher than Japan's subsequent peak, which occurred in the 1970s.

Figure 4.5 shows energy intensities for China and India measured both at market exchange rates and in terms of purchasing power parities. For both countries, energy intensities in terms of market exchange rates are very high, resembling the energy intensities of the now industrialized countries more that 100 years ago. The reason is that China's and India's GDPs are comparatively low when measured at official market exchange rates due to generally low prices in the two countries (see *Box 3.1*). Energy intensities in terms of GDP measured at purchasing power parities are generally much lower, indicating substantially higher energy effectiveness in these countries than would be calculated using official exchange rates. In terms of purchasing power parities, the peaks in commercial energy intensities may eventually prove to be lower than those experienced by the now industrialized countries.

The substantially lower energy intensity of GDP when expressed in terms of purchasing power parities ($\mathrm{GDP}_{\mathrm{ppp}}$) rather than at market exchange rates ($\mathrm{GDP}_{\mathrm{mer}}$) should be contrasted with the generally much lower energy intensity improvement rates when GDP is expressed as $\mathrm{GDP}_{\mathrm{ppp}}$ rather than $\mathrm{GDP}_{\mathrm{mer}}$. The differences can indeed be substantial. In 1990 the reported energy intensity in China was about 2.3 kgoe per US(1990)$ for $\mathrm{GDP}_{\mathrm{mer}}$ with an average historical reduction rate of 2.8% per year since 1971, compared with about 0.4 kgoe per US(1990)$ for $\mathrm{GDP}_{\mathrm{ppp}}$ for the same year. Since 1971 $\mathrm{GDP}_{\mathrm{mer}}$ has grown by 7.5% per year whereas the estimated $\mathrm{GDP}_{\mathrm{ppp}}$ has grown by 4.3% per year, roughly the same rate as total primary energy use. Caution is therefore needed when interpreting the apparent rapid energy intensity improvements, measured at market exchange rates, that are reported for some countries. As countries develop and their domestic prices

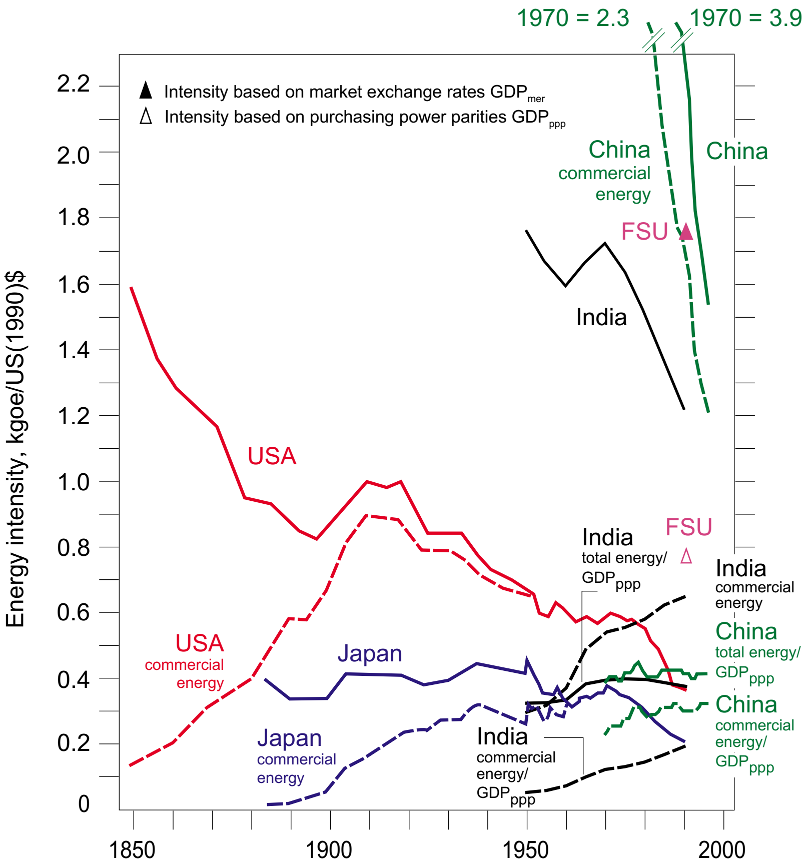


Figure 4.5: Primary energy intensity for four selected countries and FSU, total (solid lines) and commercial energy (dashed lines), in kgoe, per GDP, in US(1990)$. Unless otherwise specified, GDP refers to GDP$_{\mathrm{mer}}$. For China, India, and FSU intensities based on GDP$_{\mathrm{ppp}}$ are also given. Data sources: Nakićenović, 1987; Martin, 1988; TERI, 1994.

converge toward international levels, the difference between the two GDP measures disappears. As would be expected, energy intensity improvement rates are lower in more developed world regions.

Adding traditional energy to commercial energy reflects total energy requirements and yields a better and more powerful measure of overall energy intensity. Total energy intensities generally decline for all four countries in *Figure 4.5*. There are exceptions, including periods of increasing energy intensity that can last for a decade or two. This was the case for the USA around 1900, India during the 1960s, and China during the 1970s. Today, energy intensities are (temporarily)

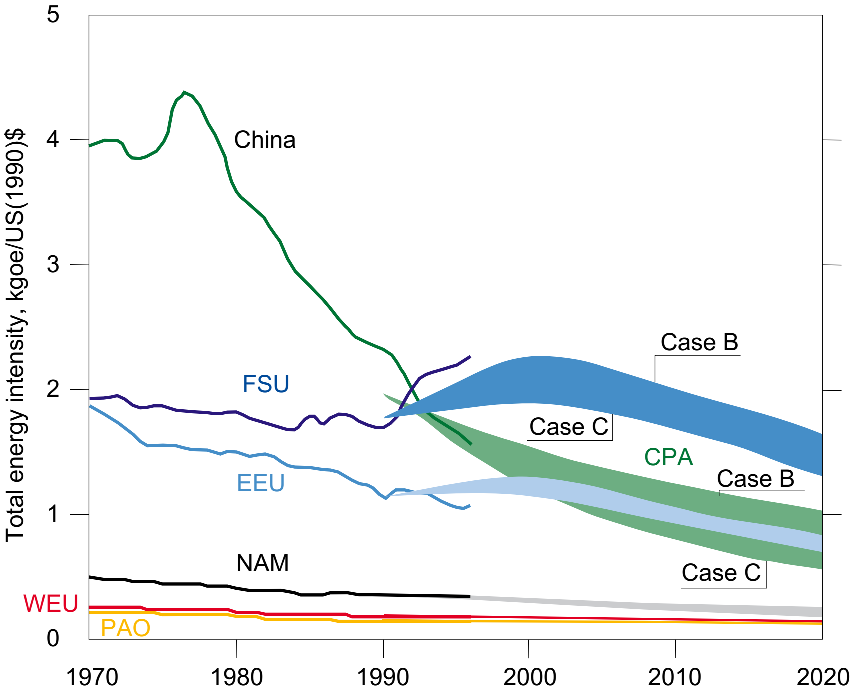


Figure 4.6: Primary energy intensities for six representative regions, including historical development from 1970 to 1996 and future ranges as reflected in the scenarios, primary energy divided by GDP in kgoe per US(1990)$. Historical data are shown for China instead of CPA as they are not available for the rest of the region.

increasing in the economies in transition due to economic depression (*Figure 4.6*). In the long run, however, the development is toward lower energy intensities. Data for countries with long-term statistical records show improvements in total energy intensities by more than a factor of five since 1800, corresponding to an average decline of total energy intensities of about 1% per year (Nakićenović, 1987).

Energy intensity improvement can continue for a long time to come. The theoretical potential for energy efficiency and intensity improvements is very large; current energy systems are nowhere close to the maximum levels suggested by the second law of thermodynamics. Although the full realization of this potential is impossible, many estimates indicate that the improvement potential might be large indeed – an improvement by a factor of 10 or more could be possible in the very long run (see Ayres, 1989; Gilli *et al.*, 1990; Nakićenović *et al.*, 1993, 1996). Thus, reduction of energy intensity can be viewed as an endowment, much like other natural resources, that needs to be discovered and applied.

In the six scenarios, improvements in individual technologies vary across a range derived from historical developments and current literature about future technological possibilities and structural change. Combined with the economic growth patterns of the three cases, the overall global average energy intensity reductions vary between about 0.8 and 1.4% per year. These figures bracket the historical rate of approximately 1% per year experienced by the more industrialized countries during the past hundred years. Cumulatively they lead to substantial energy intensity decreases across all scenarios. Energy intensity improvements are significantly higher in some regions, especially over shorter periods of time and when high economic growth rates result in fast turnover of the capital stock.

Because the six scenarios start with a base year of 1990 and were originally formulated five years ago, actual short-term trends in recent years can be compared with initial developments in the longer-term scenarios. *Figure 4.6* shows the range of the scenarios' energy intensity improvement rates for six regions compared with short-term historical trends. These range between vigorous improvements of up to 4% per year for CPA[3] and a (temporary) increase of energy intensities in the reforming economies of EEU and FSU. Overall, the scenario trajectories correctly anticipated short-term developments during the 1990s, especially for the reforming economies of Eurasia. All scenarios reflect a continuing process of successful economic reform and restructuring in all of Eurasia in the coming decades that leads to sustained investments in the energy sector and in economic development, and thus to long-term energy intensity improvements. The cases track particularly closely the recent developments in CPA, FSU, and EEU – the three regions with the most dynamic and heterogeneous changes in energy intensities.

Figure 4.7 shows shorter-term historical data since 1970 for a number of the 11 regions in terms of energy intensities versus per capita GDP. These shorter-term developments are contrasted with the experience of the USA since 1800. In all cases, economic development is characterized by a reduction of energy intensities, with the energy intensities of today's DCs at levels generally comparable with those of the now industrialized countries when they had the same per capita GDP. Different countries can follow different development paths, however, and there are some persistent differences in energy intensities even at similar levels of per capita GDP. For example, PAO and WEU have consistently lower energy intensities than NAM even at the same level of development, and apparently similar differences are emerging between SAS and CPA. Energy intensities mirror economic and technological development, geography, natural resources, and lifestyles. But history also matters in the sense that the differences between "high" and "low"

---

[3] The difference in 1990 energy intensities in *Figure 4.6* reflects the difference between China and the CPA region as a whole. Historical data are shown for China as they are not available for the rest of CPA.

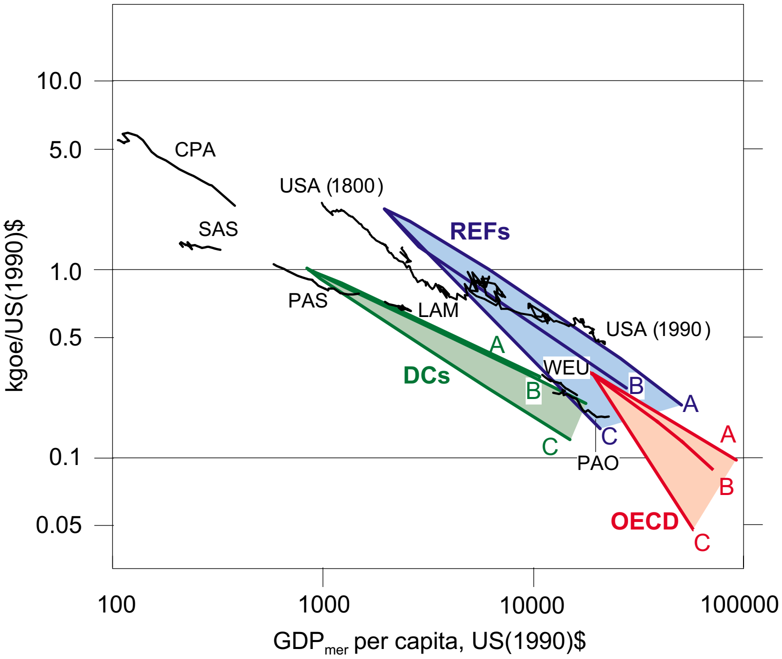


Figure 4.7: Energy intensities, in kgoe per US(1990)\$, as a function of degree of economic development, in GDP$_{\mathrm{mer}}$ per capita in US(1990)\$. Historical data (black) and Cases A, B, and C (color).

energy intensities persist for decades across different regions. The range of possibilities is reflected in *Figure 4.7* by the range between Cases A, B, and C. The energy intensity improvement paths are shown for the three macroregions as it was not possible to show the individual developments for all 11 regions in such a concise manner. Energy intensities diverge within a “cone” that starts with the 1990 energy intensity of each macroregion and widens to reflect the range of possible paths.

The conclusions that can be drawn from a full analysis of historical energy intensity changes and that are incorporated in the six scenarios for the various regions can be summarized as follows:

- Aggregate energy intensities, including noncommercial energy, generally improve over time, and this is true in all countries. A unit of GDP in the USA, for example, now requires less than one-fifth of the primary energy needed 200 years ago. This corresponds to an average annual decrease in energy intensity of roughly 1% per year. The process is not always smooth, as data from the USA and other countries illustrate. Periods of rapid improvements are interlaced with periods of stagnation. Energy intensities may even rise in the early takeoff stages of industrialization, when an energy- and materials-intensive industrial and infrastructure base needs to be developed.

- Whereas aggregate energy intensities generally improve over time, commercial energy intensities follow a different path. They first increase, reach a maximum, and then decrease. The initial increase is due to the substitution of commercial energy carriers for traditional energy forms and technologies. Once that process is largely complete, commercial energy intensities decrease in line with the pattern found for aggregate energy intensities. Because most statistics document only modern, commercial energy use, this "hill of energy intensity" has been frequently discussed. Its apparent existence in the case of commercial energy intensities, however, is overshadowed by the powerful result for the secular development of the aggregate, total energy intensities – there is a decisive, consistent long-term trend toward improved energy intensities across a wide array of national experiences and across different phases of development.

- History matters. While the trend is one of conditional convergence across countries, the patterns of energy intensity improvements in different countries reflect their different situations and development histories. Economic development is a cumulative process that, in different countries, incorporates different consumption lifestyles, different settlement patterns and transport requirements, different industrial structures, and different takeoff dates into industrialization. Thus the evolution of national energy intensities is *path dependent*. In *Figure 4.5*, for example, there is an evident distinction between the "high intensity" trajectory of the USA, and the "high efficiency" trajectory of Japan.

- Despite improvements, aggregate energy intensities for developing countries remain consistently higher (especially when GDP is measured at market exchange rates) than those in industrialized countries. However, the more important relationship is that between energy intensity and economic development, measured by either $\mathrm{GDP}_{\mathrm{mer}}$ or $\mathrm{GDP}_{\mathrm{ppp}}$ per capita. This is shown in *Figure 4.7*. Energy intensities in developing countries are similar to those of industrialized ones *at similar levels of economic development (GDP per capita).*

Given these conclusions, two "stylized facts" underlie the energy intensity trends of all three cases. First, energy intensity improvement rates are related to per capita GDP growth rates. The faster an economy grows in per capita terms, the faster its productivity growth, rate of capital turnover, and introduction of new technologies, and the faster energy intensities improve. Conversely, in cases of negative per capita GDP change, such as the recent experiences in FSU, energy intensities deteriorate. Second, there is conditional convergence among regions over time. A region at a given level of per capita GDP is assumed to achieve at least similar energy intensities as did industrialized countries when they were at similar per capita GDP levels. For example, in Case A PAS reaches US$10,000 per capita around 2040, with energy intensities that correspond to those of WEU in the early 1970s when its per capita income was at the same level.

The resulting energy intensity improvement rates for the world as a whole are 1% per year for Case A, 0.8% per year for Case B, and 1.4% per year for Case C. Such long-term improvements may appear conservative, particularly when compared with short-term energy intensity improvement rates. Part of the difference reflects the requirement in this longer-term analysis that these energy intensity improvements be sustained beyond 2020 to 2100. Another part is that the aggregate global figures mask the fact that for some regions energy intensity improvement rates are much higher than the global aggregates due to higher GDP growth rates. Energy intensity improvement rates for the three cases are illustrated in *Box 4.1* and the regional improvement rates for the three cases are presented in Chapter 7.

4.4. Technological Change

Technological change is at the heart of the productivity increases and economic growth that have allowed increases in the standard of living. Increases in performance, including energy efficiency, and cost reductions (see *Figures 4.9*, *4.10*, and *4.11*) have historically allowed economies not only to increase the quantity and quality of energy produced and delivered, but to do so with declining real costs. Technology is also crucial for easing the burden humanity imposes on the environment. We first discuss some general features of technological change and then describe how we have incorporated technological change into the scenarios.

Only recently have long-term energy models and scenarios begun to move beyond relatively simple representations of technological progress.[4] Five principal characteristics of the process can be identified:

- Innovation and experimentation with new technology in expectation of economic opportunities and profits;
- Innovation and experimentation as a hedging strategy against uncertainty of future developments;
- Continuous change and improvements through RD&D and actual “hands-on” experience (“learning by doing” and “learning by using”);

---

[4] For a comprehensive discussion see Grübler, 1998; for modeling applications see Messner *et al.*, 1996; Grübler and Messner, 1996; Messner, 1997.

- Diffusion and substitution, that is, the gradual adoption and spread of new technologies in time and space and their interaction with existing technologies;
- Impacts (social, economic, resource, and environmental) and their feedbacks on technological change.

Basic human curiosity, ingenuity, and uncertainty about the future lead individuals and institutions to explore technological frontiers, to invent, and to innovate – where by “innovation” we refer to the first practical application of an invention. The driving forces of invention and innovation also encompass uncertainty about future economic conditions (market opportunities), political and regulatory developments (constraints), natural resources, and the severity and irreversibility of environmental impacts. Following innovation, which often takes the form of development and demonstration projects in industrial laboratories, the useful services of a new technology are typically first employed in *niche markets*. These are specialty applications where a novel technology either performs a new task that cannot be accomplished otherwise or has substantial performance advantages over existing technologies even though it is most likely more expensive (see *Box 4.2*). For the gas turbines now used pervasively for power generation, the essential precursor was the jet engine introduced in military niche markets after World War II. Jet aircraft outperformed all propeller-driven planes in a niche where there was a premium on performance (speed) and cost hardly mattered.

The first commercialization in such niche markets allows suppliers and users to “learn by doing” and “learn by using,” which leads to further improvements in performance and cost (see *Box 4.2*). Use in a wider array of markets, or *pervasive diffusion*, follows as the new technology replaces older competitors. For example, after military applications jet engines found their way into commercial aircraft, first the Comet in England and then the Boeing 707 in the USA – a step that dramatically changed long-range civil aviation. In parallel, the first stationary gas turbines were developed as derivatives of jet engine technology. They were expensive and could not match the performance of steam turbines in generating electricity, but found a niche market providing peak power. Development continued, highly efficient combined cycle designs were introduced, installed capacity expanded, and today gas turbine technology is the most efficient way to generate electricity as well as the cheapest when the transport infrastructures are in place. Close to four decades have passed between the first application of gas turbines in military niche markets and their perfection to a preferred technological option for power generation, that is, their pervasive diffusion. This diffusion has been helped along the way by changing market conditions which now favor technologies that emit little pollution and have low capital costs. At the same time, partly due to this diffusion of gas turbines, the deregulation and liberalization of markets have been promoted by the availability of a low capital-cost capacity. This emphasizes the importance of uncertainty – about market conditions and diffusion in this case – which both motivates experimentation in the first place and then combines with performance and cost improvements gained through experience to turn some innovations into business and social successes, but many more into historical curiosities.

The typical resulting pattern of a technology's market share over time is an S-shaped curve.[5] At the earliest stage of commercialization, growth in a technology's market share is slow as the technology is applied only in specialized niche markets and costs are high. Growth accelerates as early commercial investments lead to compounding cost reductions and standard-setting, which leads to imitation and adoption in a wider array of settings and thus to pervasive diffusion. As the potential market is saturated and a product matures, growth in market share declines to zero. With the arrival of better competitors, the market share of the senescent technology declines.

The evolution of technological systems is as important as the evolution of individual new technologies. As the use of an individual technology, such as the automobile, expands, its evolution becomes intertwined with the evolution of many other technologies and institutional and social developments. The evolution of automobiles both affects and is affected by what happens to a host of component suppliers and their technologies. It affects and is affected by the expansion of infrastructures such as road networks and the system for refining and distributing petroleum products in gas stations. And it affects and is affected by social and institutional developments, such as settlement patterns, business adaptations to changed transportation options, and training institutions for both drivers and mechanics.

As a new technology prompts adaptations among potential component suppliers and influences related infrastructural developments, it gains advantages that will make it more difficult for subsequent competitors to catch up. A particular technological configuration becomes "locked-in" and its future development becomes "path dependent" (Arthur, 1983 and 1989) as changes build on previous ones and radical change becomes ever more difficult to implement. The same is true institutionally. The more schools, businesses, and individuals that use Microsoft (and the QWERTY keyboard), the more likely it is that the next school, business, or individual will also choose Microsoft.

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. Second, learning and lock-in

---

[5] See Schumpeter, 1939; Marchetti and Nakićenović, 1979; Freeman, 1983; Vasko *et al.*, 1990; Nakićenović and Grübler, 1991; Grübler and Nakićenović, 1991; Grübler, 1996.

Box 4.2: Technological progress and learning curves

Technology costs and performance – including energy efficiency in particular – improve with experience, and there is a pattern to such improvements common to most technologies. Initially, costs are high due to batch production modes requiring highly skilled labor. Performance optimization and cost minimization are rarely important, with the overriding objective being the demonstration of technical feasibility. When the technology seeks entry into a market niche, costs begin to matter, although the technology's ability to perform a task that cannot be accomplished in any other way is usually of central importance. Examples are fuel cells in space applications, photovoltaic systems for remote and unattended electricity generation, gas turbines for military aircraft propulsion, and drill bit steering technology.

Niche markets, however, are not sufficient to reach commercialization. Improvements need to be made in reliability, durability, efficiency (*Figure 4.9*), and, most important, cost (*Figure 4.10*). Any RD&D devoted to these objectives creates a *supply push*. Complementing the *supply push*, there must be a *demand pull* by which initial markets are sufficiently expanded to further reduce costs through economies of scale. The *demand pull* may well be policy driven. Technically feasible technologies that are not yet economically competitive might benefit from environmental or energy security policies that increase their competitors' costs. For example, other electricity generation options benefit from requirements for flue gas desulfurization in coal-fired plants, or from bans on electricity generation from natural gas that restrict combined cycle gas technology.

There are steep cost improvements during the RD&D phase. For example *Figure 4.11* shows a 20% reduction in investment costs per doubling of cumulative production in the case of gas turbines. These are followed by more modest improvements after commercialization – for gas turbines, some 10% per production doubling. Improvements continue for a while at a slower pace and then cease as the technology approaches the end of its life cycle.

This pattern of diminishing costs with increasing experience is the "learning" or "experience" curve (Argote and Epple, 1990). Its specific shape depends on the technology but is a persistent characteristic of *all* successful technologies. Modular and small-scale mass-produced products usually have steeper learning curves than do large complex technologies built in the field. This is shown in *Figure 4.11* for photovoltaics, windmills, and gas turbines, all of which display similar learning-curve effects. New technologies may also benefit from economies already achieved by older technologies. The existing transmission infrastructure, for example, can be readily used by new electricity generating technologies.

make technology transfer more difficult. 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, repairmen, training programs, and so forth, and by an infrastructure that has coevolved with the technology, will be much less effective in isolation.

Technological progress is central to all three sets of scenarios – Cases A, B, and C – and a principal conclusion of this study is that the long-term future (after 2020) will largely be determined by the technological choices made in the next few decades. In constructing the three cases, it was therefore necessary not to treat technology as static, but to incorporate anticipated future characteristics and improvements – such as performance, cost, and diffusion – of new energy technologies such as photovoltaics, hydrogen production, and fuel cells.

We took a novel approach in which we pooled all available technology data into a single data bank, from which medians and ranges could then be extracted. The data bank used for our analysis (see Messner and Strubegger, 1991; Messner and Nakićenović, 1992; Strubegger and Reitgruber, 1995) now includes some 1,600 technologies that together cover the whole energy system from primary energy extraction to end-use conversion. For example, representative investment costs for solar systems and nuclear reactors were derived from 45 and 34 independent estimates, respectively (*Figure 4.8*). Near-term technology costs assumed for the three cases were derived from the medians of the empirical cost distributions. Lower ranges defined the scope for the future cost reductions that occur at different rates in the three cases: optimistic in Cases A and C, and more cautious in Case B (see *Figures 4.10* and *6.1*).

Cases A, B, and C incorporate technological change through different learning-curve effects for various individual and generic technologies (see *Box 4.2*), reflecting different priorities for RD&D, socioeconomic development, and energy system requirements. Technology in our cases is not a free good but instead is the result of deliberate search, experimentation, and implementation, directed by both social and political policies as well as economic opportunities and profit expectations. Through technological change, upward cost pressures facing future energy systems can be mitigated. Measured either by overall energy systems or macroeconomic costs, technology improvements can yield large returns on investments. However, they are not free, requiring RD&D, entrepreneurship, and appropriate incentives and policies to progress from the initial design stage through early implementation in niche markets to full market potential and widespread diffusion.

Within each case, there are also differences between industrialized and developing regions for technologies that are manufactured domestically. For technologies that are internationally traded, costs are assumed to be uniform across regions.

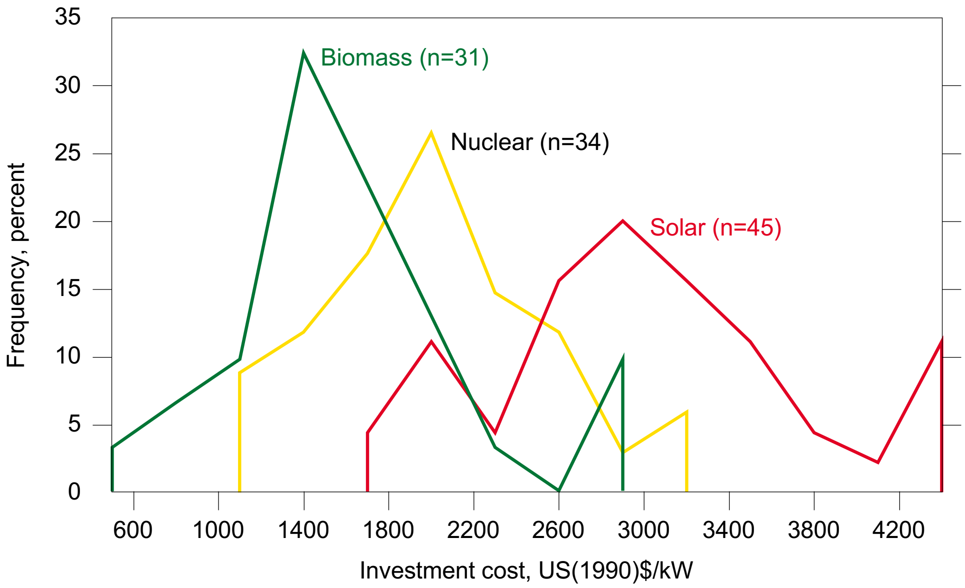


Figure 4.8: Range of investment cost distributions from the IIASA technology inventory for biomass, nuclear, and solar electricity generation used as input to assess costs of current and future energy systems, in US(1990)$ per kW.

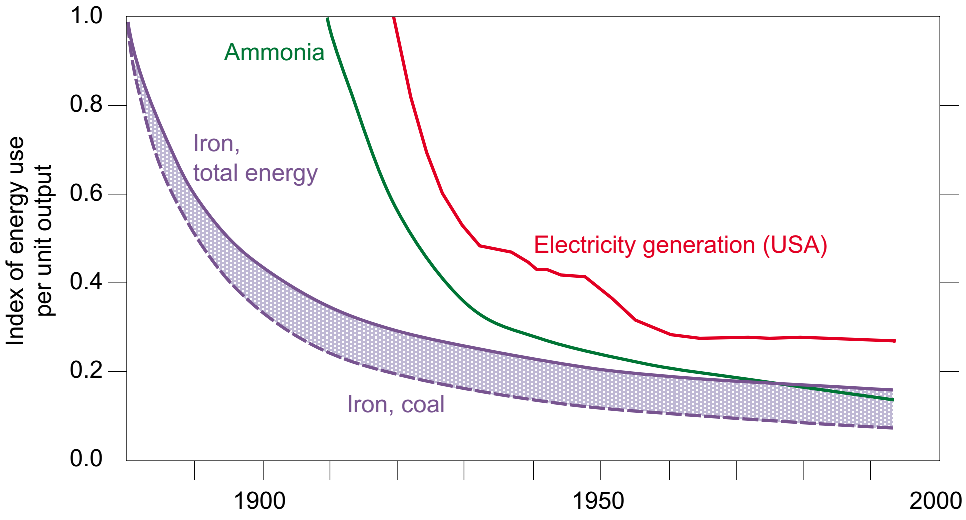


Figure 4.9: Technology improvements: The example of energy input for production of iron, ammonia, and electricity shown as an index with energy input at introduction equal to 1. Sources: adapted from USDOC, 1975 and consecutive volumes; Marchetti, 1978; Grübler, 1990.

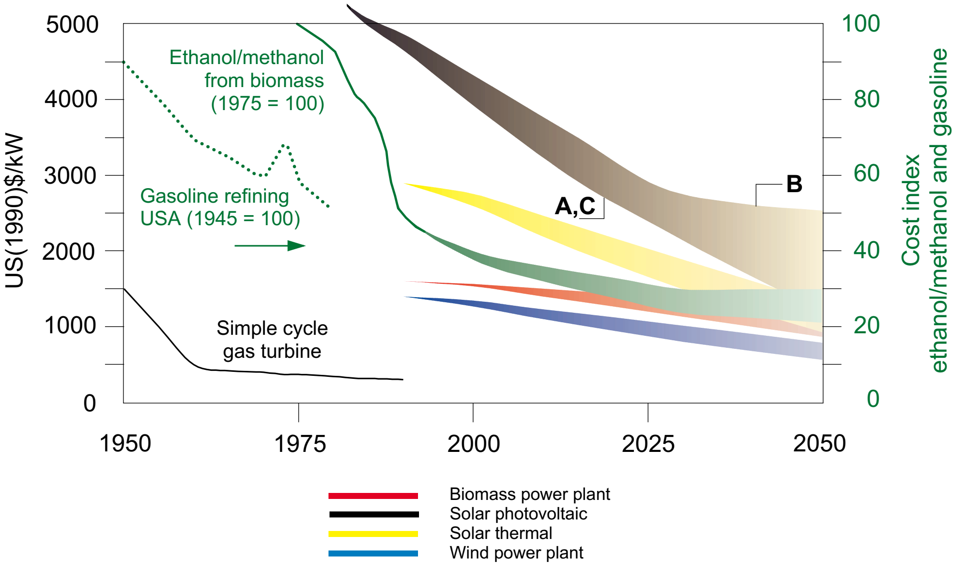


Figure 4.10: Technology cost improvements, in US(1990)$ per kW. Past achievements for US gasoline refining (Fisher, 1974) and Brazilian ethanol/methanol (Goldemberg, 1994) and range for biomass, solar, and wind electricity generation assumed for the three cases.

In all cases, energy options that are not technically feasible today are excluded. Nuclear fusion, for example, is excluded, while hydrogen is included as an energy carrier because it can be produced with current technologies, although not yet at competitive costs. New and emerging technologies are kept as generic as possible. Stationary fuel cells, for example, are represented as one technology: we do not distinguish between solid oxide, molten carbonate, phosphoric acid, and solid polymer fuel cells. Similarly, advanced coal-fired electricity generation is considered a single technology, with no distinction being made between integrated gasification combined cycle and pressurized fluidized bed technology. For synfuels from coal or biomass, we assume methanol as an energy vector, although in some regions ethanol may be the fuel of choice.

In Case A, there are substantial learning-curve effects for all new, and currently marginal, energy production and conversion technologies. Thus there are considerable advances in hydrocarbon exploration and extraction, 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 and environmentally desirable technologies. However, they lag on average 30% behind those in Case A, which is consistent with the less concerted RD&D efforts in Case B.

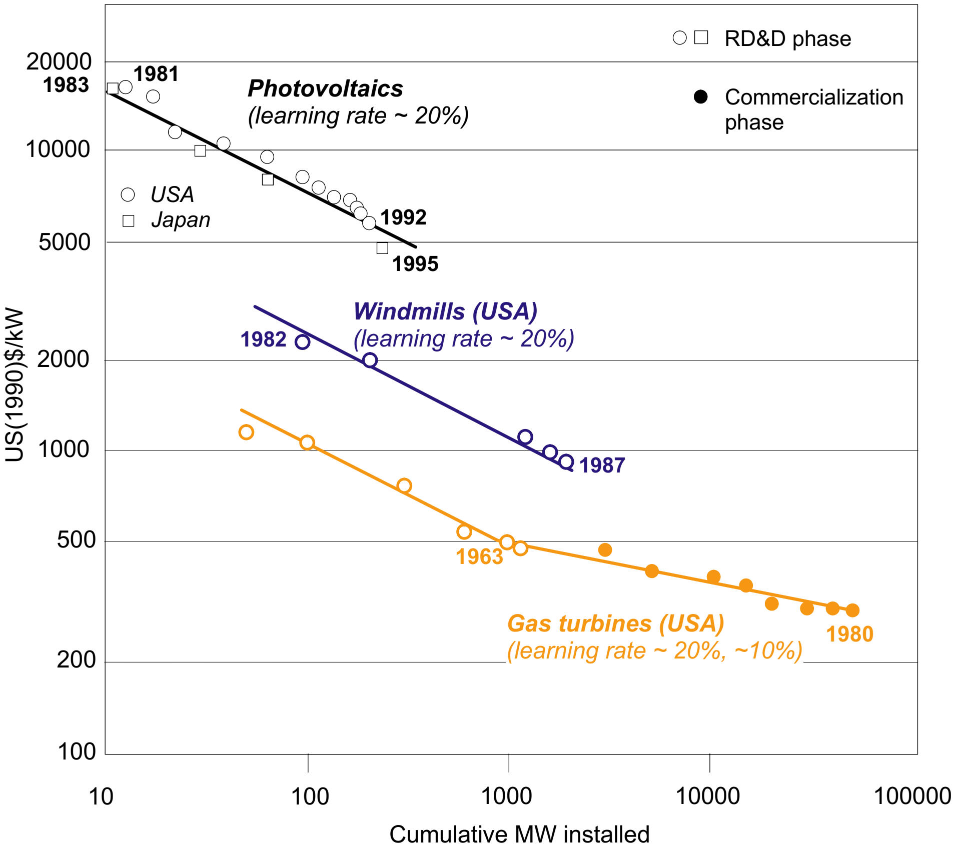


Figure 4.11: Technology learning curves: Cost improvements per unit installed capacity, in US(1990)$ per kW, versus cumulative installed capacity, in MW, for photovoltaics, wind, and gas turbines. Sources: adapted from MacGregor *et al.*, 1991; Christiansson, 1995.

For Case C, learning-curve effects by design favor 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.

4.5. The Resource Base

Energy resources have obvious implications for future energy system development. In presenting the estimates of this study, we use the terminology proposed by McKelvey (1972) and Fettweis (1979). Resources are classified according to a two-dimensional matrix. One axis represents decreasing geological certainty of occurrence. The other represents decreasing economic recoverability. For energy, the term “occurrence” covers all types and forms of hydrocarbon deposits, natural uranium, and thorium in the earth’s crust.

Identified occurrences have the highest geological assurance, followed by inferred and speculative occurrences. *Reserves* are those occurrences that are known and are recoverable with present technologies at prevailing market conditions. *Resources* are occurrences that are distinct from reserves in that they have less certain geological assurance or lack present economic feasibility, or both. Changing market conditions, innovation, and advances in geosciences can transform resources into reserves. The *resource base* is the sum of reserves and resources. It includes all potentially recoverable coal, conventional oil and natural gas, unconventional oil resources (such as oil shale, tar sands, and heavy crude), and unconventional natural gas resources (such as gas in Devonian shale, tight sand formations, geopressured aquifers, and coal seams). Quantities that are not considered potentially recoverable are classified as “additional occurrences” and are excluded from the resource base of future, potentially recoverable resources. Occurrences include methane hydrates and natural uranium dissolved in seawater. Both are known to exist in enormous quantities, but there is great uncertainty about their extent and the eventual technology and economics of their recovery.

Typically, unconventional sources differ from conventional sources by one or more of the following characteristics:

- They occur in significantly lower concentrations.
- They require unusual or extreme technological prerequisites for their recovery.
- They need complex and capital-intensive conversion for modern-day use.
- They have significant environmental implications.

Given the large quantities of conventional oil and gas reserves and resources, the actual resource dimensions of unconventional oil and gas (not to mention additional occurrences) have received relatively little attention.

Box 4.3 summarizes recent estimates of reserves and recoverable resources of oil, gas, and coal as reported by IIASA (Rogner, 1997), IPCC (Nakićenović *et al.*, 1996), the US Geological Survey (Masters *et al.*, 1994), and WEC (1992, 1993, 1998). We also give a summary of the global nonrenewable energy resource base and compare cumulative historical and 1990 consumption levels of fossil energy and natural uranium with estimates of reserves, resources, and additional occurrences. Driven by economics, technological and scientific advances, and policy decisions, this resource base has expanded over time, and reserves have been continuously replenished from resources and from new discoveries (see Masters *et al.*,

Box 4.3: Estimates of energy reserves, resources, and occurrences

Table 4.4: Global fossil and nuclear energy reserves, resources, and occurrences, in Gtoe.

	Consumption[a]				Resource	Additional
	1850 to 1990	1990	Reserves[b]	Resources[c]	base[d]	occurrences
Oil						
Conventional	90	3.2	150	145	295	
Unconventional	–	–	193	332	525	1,900
Natural gas						
Conventional[e]	41	1.7	141	279	420	
Unconventional	–	–	192	258	450	400
Hydrates[f]	–	–	–	–	–	18,700
Coal[g]	125	2.2	606	2,794	3,400	3,000
Total[h]	256	7.0	1,282	3,808	5,090	24,000
Uranium[i]	17	0.5	57	203	260	150
in FBRs[j]	–	–	3,390	12,150	15,540	8,900

Note: – negligible amounts; blanks, data not available.
[a] Grübler and Nakićenović, 1992.
[b] Masters *et al*., 1994; IPCC, 1996b; OECD/NEA and IAEA, 1995; WEC, 1993.
[c] Resources to be discovered or developed to reserves. Masters *et al*., 1994 (upper range); IPCC, 1995; OECD/NEA and IAEA, 1995.
[d] Resource base is the sum of reserves and resources.
[e] Includes natural gas liquids.
[f] MacDonald, 1990; Kvenvolden, 1988, 1993.
[g] WEC, 1993.
[h] All totals have been rounded.
[i] OECD/NEA and IAEA, 1995.
[j] FBRs = fast breeder reactors.
Sources: Rogner, 1997; Nakićenović *et al*., 1996; Masters *et al*., 1994; Nakićenović *et al*., 1993; WEC, 1992; Grübler, 1991; MacDonald, 1990; Rogner, 1990; BP, 1995 and earlier volumes; BGR, 1989; Delahaye and Grenon, 1983.

Table 4.5: WEC estimates of reserves and ultimately recoverable resources, in Gtoe and 1,000 tons uranium (tU).

	Proved reserves	Ultimately recoverable
Conventional oil	150	200
Unconventional oil	–	511–595
Conventional gas	133	220
Coal and lignite	430	3,400
Total	713	4,331–4,415
Uranium in 1,000 tU	3,400	17,000

Sources: WEC, 1993, 1998.

Table 4.6: US Geological Survey estimates of reserves of conventional oil and gas, in Gtoe.

	Identified	Future discoveries with probability of		
	reserves	95%	50%	5%
Conventional oil	150	36	74	145
Conventional gas	129	68	126	265
NGL[a]	12	–	14	–
Total	291	104	214	410

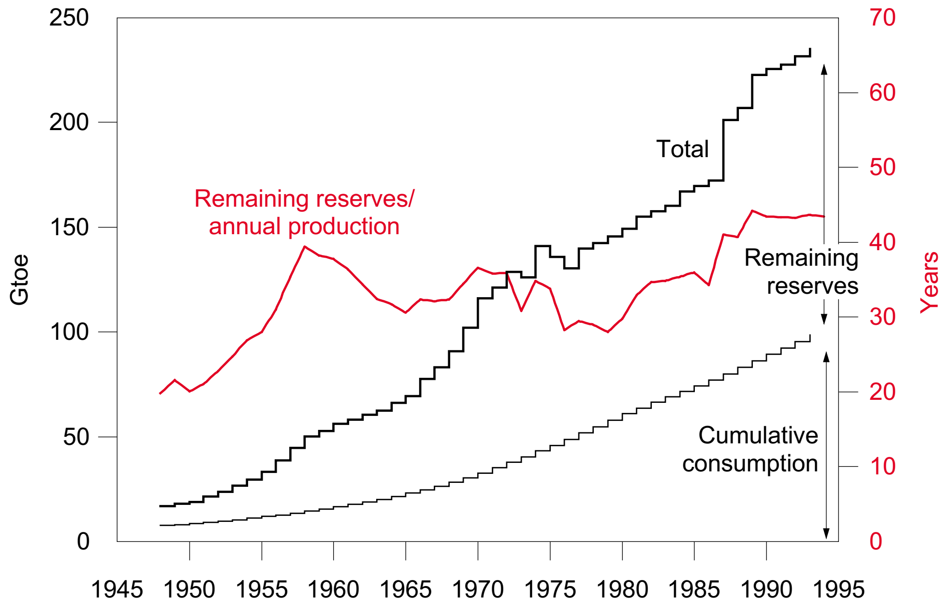
Source: Masters *et al*., 1994.
[a] NGL = Natural gas liquids.

1991, 1994). *Figure 4.12* shows the history of oil and gas reserves, for example, and increases in reserve-to-production ratios in the past four decades. Reserve additions have shifted to inherently more challenging and potentially costlier frontier locations, with technological progress outbalancing potentially diminishing returns. However, with reserve-to-production ratios above 40 years, there is little economic incentive for private sector industries to explore and vigorously develop more reserves.

We expect the resource base to continue to expand in the future. But no one can anticipate how market conditions, knowledge, exploration methods, and production technologies will continue to change. Furthermore, we cannot continue to express complex concepts such as the resource base by simple measures or single numbers. The inherent difficulty is well expressed by Adelman (1992), who describes energy resource assessment as an effort “in estimating the potentially economic portion of an unknown total.”

In this study, the “resource base” column in *Table 4.4* in *Box 4.3* is taken as the availability range of nonrenewable energy sources. The “reserves” column represents the fraction of the resource base that is recoverable today, that is, can be produced with current technology under present market conditions. The resource base in turn includes those resource quantities that, with technical progress, could become economically attractive within the study horizon and that could become potentially available over the long term (i.e., beyond 2020). Because of the uncertainty about the ultimate potential of the fossil resource base, its availability is varied across the cases, and the scenarios vary from conservative (Case C), or cautious (Case B and Scenario A2), to optimistic (Scenarios A1 and A3). The “additional occurrences” listed in the far right column are not included in any of the three cases or their scenarios. They do indicate, however, that if resource exhaustion were the only criterion, the world would be unlikely to run out of nonrenewable energy sources any time before the 22nd century.

The fossil reserves as listed in *Table 4.4* amount to 1,300 Gtoe, and the fossil resource base (including reserves) is estimated at approximately 5,000 Gtoe. That is certainly sufficient for more than 100 years, even in the high-energy Case A scenarios. Thus, while the next 100 years may bring temporary and structural energy shortages, there is no expectation that we will be limited by absolute resource constraints. However, the consumption of such large quantities of fossil energy represents a considerable technological and investment challenge and would translate into cumulative carbon emissions corresponding to six to seven times the current atmospheric carbon content of about 760 GtC (or CO_2 concentration of 358 parts per million by volume, ppmv). Therefore, concerns about economic recoverability and the environment are more likely to cause a future shift to other sources of energy than are absolute resource constraints.



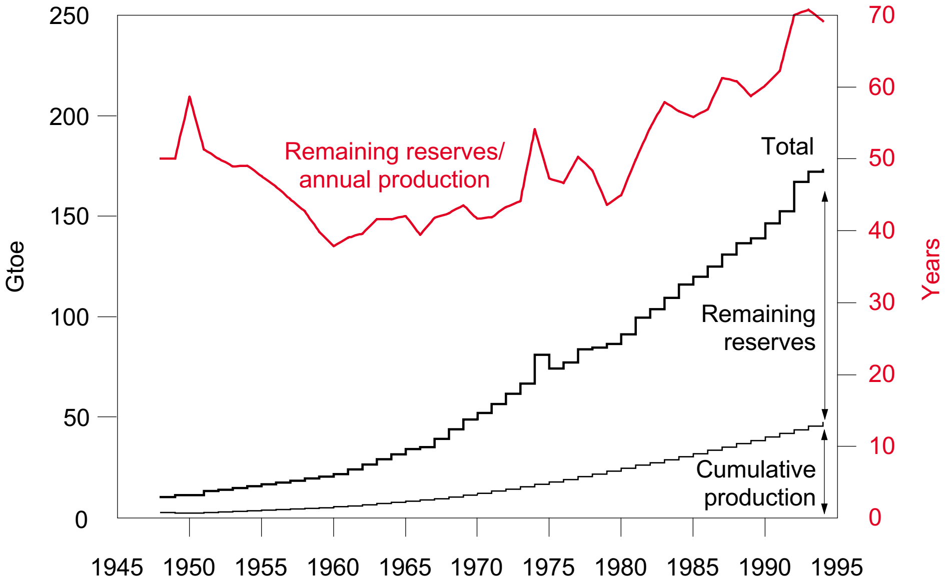


Figure 4.12: Technically and economically recoverable reserves and cumulative production of (*top*) conventional oil and (*bottom*) natural gas, in Gtoe. The increase in the reserve base despite growing production (i.e., the continuous replenishment of reserves from resources) is reflected in the stable or increasing reserve-to-production ratios shown in the figure.

Box 4.3 also includes figures for uranium. As shown at the bottom of *Table 4.4*, the energy effectiveness of uranium depends greatly on the conversion technology used, but the resources are potentially extremely large. Nuclear energy's future will depend on, among other things, how current controversies concerning safety, waste disposal, and proliferation are resolved. The successful development of new technologies that resolve these issues is likely to play a much more important role in the future of nuclear power than will resource constraints.

The resource situation for renewable energies is quite different from that of fossil energy or uranium. Rather than being a (finite, albeit large) stock variable, the resources of renewables are characterized by huge – yet dispersed and diffuse – annual flows of energy available in the environment. With few exceptions (like some hydropower sites), renewable resources offer *energy densities* orders of magnitude lower than those of deposits of fossil fuels in the form of coal mines or oil fields. As an extreme illustration, the peak power requirement in Manhattan is of the order of 1.5 kW per m^2, with an average of 0.2 kW or 1,750 kilowatt hours (kWh) per m^2 per year (Bowman, 1995), which is up to 10 times larger than the mean direct solar radiation onto New York City (0.15 kW per m^2; WEC, 1994). Not unlike fossil energy sources, therefore, "new" renewables also require elaborate systems of energy conversion, transport, and distribution to "bridge" spatially separated areas of energy supply and demand. The limitations of renewables are therefore not constraints imposed by the magnitude of the energy flows available in the environment, which are indeed gigantic, but rather how these diffuse flows can be harnessed and converted to fuels required to provide energy services.

Renewable resources are characterized by three major advantages. First, they can provide energy services on an indefinite basis given that their use does not fundamentally disturb natural energy flows. Second, they can do so without major alterations of global geochemical cycles, being either carbon free (solar or hydropower) or carbon neutral (sustainable use of biomass). Finally, they can provide energy for numerous generations to come, and – at least in principle – for any level of future energy demand, as the natural energy flows are indeed large by any standards. The earth intercepts about 130,000 Gtoe of solar energy annually compared with 9 Gtoe total global energy consumption in 1990. *Figure 4.13* provides a schematic illustration of annual global energy flows without anthropogenic disturbances.

Clearly, only a fraction of these flows could be practically used for energy purposes. This in itself is not a problem, as all conceivable human energy needs could be provided for by diverting only a small fraction of the solar influx to energy use. Renewable potentials are limited by numerous factors such as mismatch between power densities and locations of energy supply and demand, possible land-use conflicts, adverse local environmental impacts, capital costs, or infrastructure

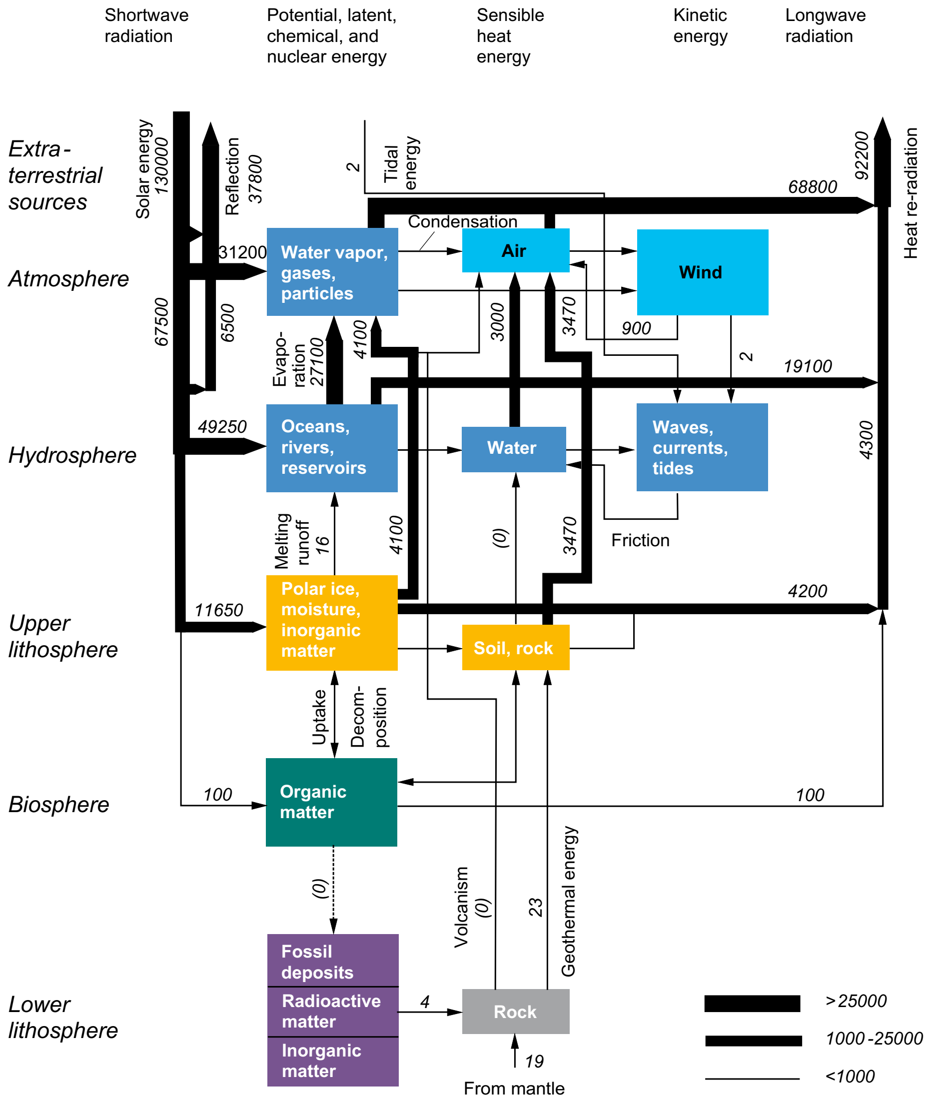


Figure 4.13: Renewable energy flows, in Gtoe. Source: Sørensen, 1979.

requirements. The renewable potentials that could be realized with current technologies and economics can be compared with fossil energy reserves, while the maximum technical potentials that could be developed under favorable future technological and economic conditions can be compared with the concept of the fossil "resource base."

The IPCC in its Second Assessment Report identifies global renewable potentials by the 2020s in the range of 3.2 to 5.6 Gtoe per year and the long-term technical potentials beyond 2020 at up to 100 Gtoe per year (Nakićenović *et al*., 1996). Other estimates include the WEC *New Renewable Energy Resources* (WEC, 1994) report, which gives a range of renewable energy potentials reaching 3.3 Gtoe per year by 2020, and *Energy for Tomorrow's World* (WEC, 1993), which identifies renewable energy potentials (in the Epilogue) of up to 13 Gtoe by the year 2100, of which 10 Gtoe could be supplied by "new" renewables. These so-called new renewables do not include the traditional renewable sources – such as large hydropower – or the traditional uses of fuelwood and agricultural wastes.

Thus, renewable energy sources have the promise of meeting most human energy needs in the long term, but their actual contribution is likely to be much more modest in the shorter term. There is obviously a wide range of uncertainty on the possible timing and extent of the diffusion of renewables. Only with major, effective, and internationally coordinated policy support could developments be accelerated and significant inroads into total primary energy supply be made in the next two to three decades. Conversely, over more distant time horizons, the potentials for renewables increase significantly. Technology improvements can ultimately bring the cost of renewable energies down to competitive levels, whereas the cost of traditional (fossil) energies is likely to increase in the long term due to both the exhaustion of their technology improvement potentials and the eventual shift to lower-grade and higher-cost resources.

4.6. Environment

Concerns about the environmental impacts of energy production and consumption are not new. Complaints about air pollution from burning "sea coal" date back to the 13th century in England. With the advent of industrialization and its resulting concentration of energy consumption in urban and industrial areas air and water pollution began to exceed the assimilative capacities of local environments on a large scale and became major issues. For developing countries, air pollution from industrialization has now joined traditional indoor air pollution as a major challenge. At the same time, environmental concerns in the industrialized countries have shifted more toward very long-term and global issues, most prominently climate change.

The type and extent of pollution are closely related to the degree of economic development and industrialization, as is illustrated in *Figure 4.14*. To some extent, economic development enables societies to successfully address environmental problems of both poverty (such as inadequate sanitation or indoor air pollution from traditional biomass use) and industrialization (such as sulfur emissions). But economic development and affluence can also generate new environmental problems, such as waste disposal and possible global warming.

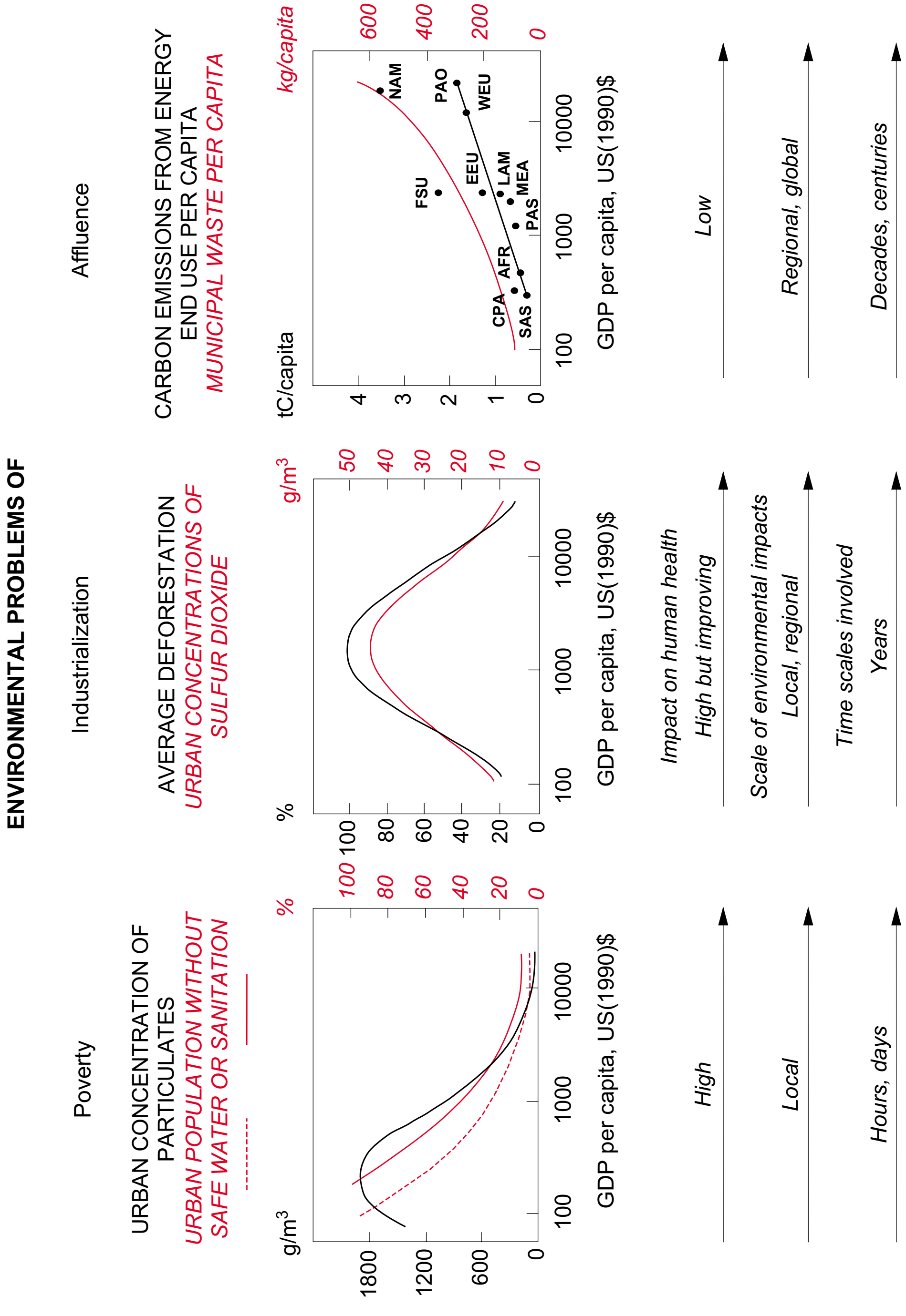


Figure 4.14: A typology of environmental problems as they evolve with economic development. Source: adapted from World Bank, 1992.

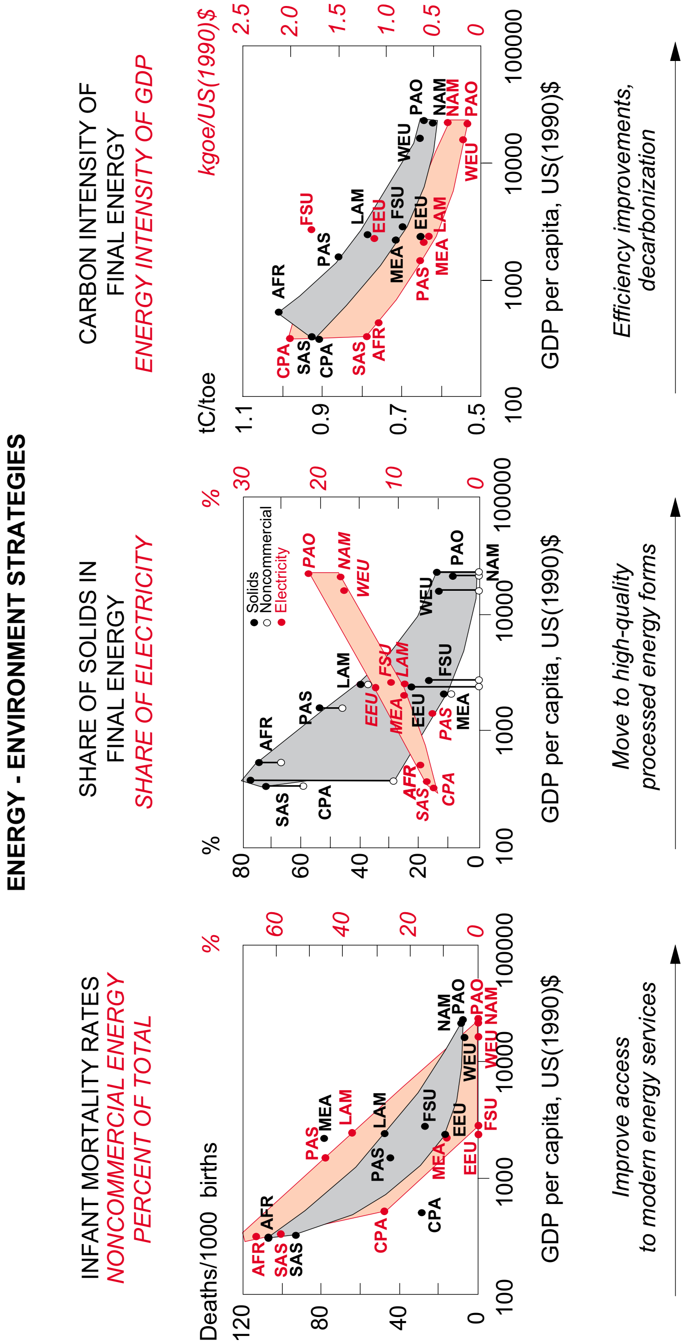


Figure 4.15: Energy strategies to address environmental problems of poverty, industrialization, and affluence. Improvements in energy efficiency and structural change in energy systems toward cleaner energy carriers (“decarbonization”) are important generic long-term strategies to tackle environmental problems.

Local impacts, including indoor air pollution, have been and continue to be a major environmental concern related to energy use. Indoor and outdoor air quality were important in Victorian London and are equally important for many megacities of the developing world today. The cause is basically the same now as then: emission-intensive fuels, such as coal and wood, burned in inefficient open fireplaces and cookstoves. In industrialized countries, these problems have been successfully resolved in three ways: first, by the use of more efficient end-use devices (e.g., central-heating systems and fuel-efficient stoves); second, by more complete combustion within these devices; and third, by the shift to clean (often grid-dependent) fuels such as electricity and gas (see *Figure 4.15*). Compared with the historical reductions in environmental impacts through these sorts of changes in efficiencies and fuels, "end-of-pipe" environmental solutions applied to large point sources are recent phenomena.

Despite major reductions in local air pollution problems in the industrialized world, these problems remain acute in the developing world. More than one billion people in developing world cities are exposed to unacceptably high ambient concentrations of suspended particulate matter and sulfur dioxide (SO_2), significantly exceeding World Health Organization (WHO) guidelines (World Bank, 1992). The situation with transport-related air pollution is also dramatic in many cities of the developing world. It is estimated that people in the poorest countries are exposed to air pollution levels orders of magnitude higher than those in the industrialized countries, despite the fact that the latter are using orders of magnitude more energy. Due to cooking on open wood fireplaces, indoor air pollution in poor rural areas is more than 20 times higher than in industrialized countries (Smith, 1993). Particulate concentrations in urban areas of the developing world can be more than five times those in OECD cities (WHO, 1992). That more time is spent outdoors because of the climate and inadequate housing conditions only serves to compound the problem. Consequently, pollution exposure both indoors and in urban areas can be up to a factor of 20 higher in developing countries than in industrialized ones (Smith, 1993).

Local environmental problems should thus have first priority. As in the past, the most effective solutions will be those that are most comprehensive, relying on a mix of efficiency improvements, cleaner fuels, and "end-of-pipe" control technologies. Both efficiency improvements and the shift to cleaner fuels will yield triple dividends: lower resource use, lower overall energy system costs, and lower emissions. Past structural changes in the energy system have moved in exactly these directions, although not yet quickly enough to offset the vast expansion of human activities. This is illustrated in *Figure 4.16* where the carbon intensity of primary energy over time is taken as an indicator of other pollutants. (Sulfur and, in many cases, NO_x emissions are generally higher for high-carbon fuels such as

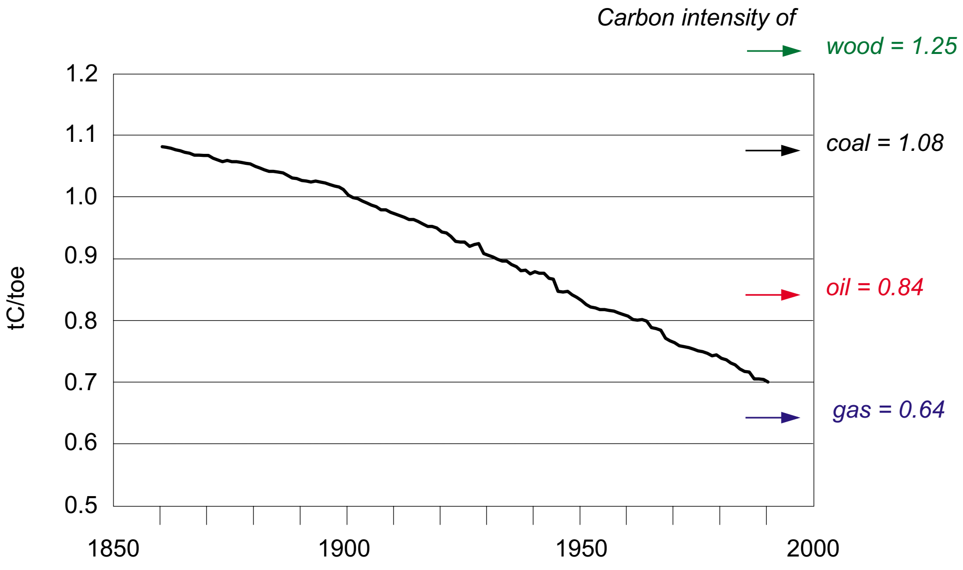


Figure 4.16: Carbon intensity of world primary energy mix, 1850 to 1990, in tC per toe, including emissions from unsustainable uses of fuelwood. Source: Nakićenović *et al*., 1996.

coal.) Although the decarbonization of the world's energy system shown in *Figure 4.16* is comparatively slow at 0.3% per year, the trend is consistent and in the right direction. Measured in terms of final energy, progress has been quicker due to the increasing use of clean, grid-dependent energy carriers such as electricity, district heat, and gas.

The next chapter addresses the question of whether the trend of *Figure 4.16* can continue. The answer is "yes." Indeed, we expect that all possible energy futures covered by our three cases are capable of maintaining favorable decarbonization trends for final energy and, with the exception of Scenario A2, also for primary energy.