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IIASA Working Paper

WP-95-102

September 1995

Grubler, A., Jefferson, M. and Nakicenovic, N. (1995) A Summary of the Joint IIASA and WEC Study on Long-Term Energy Perspectives. IIASA Working Paper. WP-95-102 Copyright © 1995 by the author(s). http://pure.iiasa.ac.at/4494/

Working Paper

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International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 807 □ Fax: +43 2236 71313 □ E-Mail: info@iiasa.ac.at

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Arnulf Grübler,* Michael Jefferson,** and Nebojša Nakićenović*

Abstract

The paper reports on a study on *Global Energy Perspectives to 2050 and Beyond* conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC). All together three cases of economic and energy developments were developed that sprawl into six scenarios of energy supply alternatives extending until the end of the 21st century. The internal consistency of the scenarios was assessed with the help of formal energy models. The study took close account of world population prospects, economic growth, technological advance, the energy resource base, environmental implications from the local to the global level, financing requirements, and the future prospects of both fossil and non-fossil fuels and industries. Although no analysis can turn an uncertain future into a sure thing, the study identifies patterns that are robust across a purposely broad range of scenarios. The study also enables to relate alternative near term research and development, technology, economic, and environmental policies to the possible long-term divergence of energy systems structures. Due to the long lead times involved in the turnover of capital stock and infrastructures of the energy system, policies would need to be implemented now in order to initiate long-term structural changes in the energy system that would however become significant only after the year 2020.

INTRODUCTION

This paper summarises a study of long-term energy prospects conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC). The study report *Global Energy Perspectives to 2050 and Beyond* [1] was presented at the 16th WEC Congress in Tokyo, October 1995.

The study is based on the formulation of alternative scenarios, corroborated by an integrated assessment framework of energy-environmental models under development at IIASA (for an overview see the Appendix I on methodology). The 1993 WEC Commission report *Energy for Tomorrow's World* [2] outlined global energy perspectives and related issues in some detail to the year 2020. The Commission report's broader outline to 2100 served as a starting point of the analysis reported here.

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*Arnulf Grübler is a Research Scholar in the Environmentally Compatible Energy Strategies Project at the International Institute for Applied Systems Analysis (IIASA) Laxenburg, Austria. Nebojša Nakićenović is the Project Leader of the Environmentally Compatible Energy Strategies Project at IIASA and is also the Director of the joint IIASA and WEC Study on "Long-Term Energy Perspectives", World Energy Council (WEC).

**Michael Jefferson is Deputy Secretary General of the World Energy Council (WEC), London, United Kingdom.

An earlier version of this paper was published as a support paper for the Session on "Energy Perspectives to 2050" at the 16th World Energy Council (WEC) Tokyo Congress held on 8–13 October 1995.

Table 1: A summary for three cases in 2050 and 2100.

	Case		
	A High Growth	B Middle Course	C Ecologically Driven
Population in 10^9			
2050	10.1	10.1	10.1
2100	11.7	11.7	11.7
GWP[a] in 10^{12}\$			
2050	100	75	75
2100	300	200	220
Energy intensity decline	medium	low	high
PE/GDP, %/yr			
World (1990–2050)	−1.0	−0.7	−1.4
World (1990–2100)	−1.0	−0.8	−1.5
Primary energy demand, Gtoe			
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
CO_2 emission constraint	no	no	yes
Carbon emissions, GtC			
2050	9–15	10	5
2100	7–22	14	2
Environmental taxes	no	no	yes
Number of scenarios	3	1	2

[a] Gross World Product

The Cases/Scenarios

Three alternative cases of long-term economic and energy developments were used to explore alternative possible futures. The cases are labelled A (High Growth), B (Middle Course), and C (Ecologically Driven). The key features of the three cases are summarised in Table 1.

In the early stages of the study it became apparent that it was necessary to move beyond the formulation of three alternative cases. More possibilities opened up than originally anticipated and the three cases blossomed into six scenarios of energy supply systems alternatives. Three variants of Case A (Scenarios A1, A2 and A3) and two variants of Case C (Scenarios C1 and C2) were developed. For the Middle Course Case B only one scenario was developed as it was designed to represent a future characterized by incremental and gradual changes.

The three cases have a number of common features:

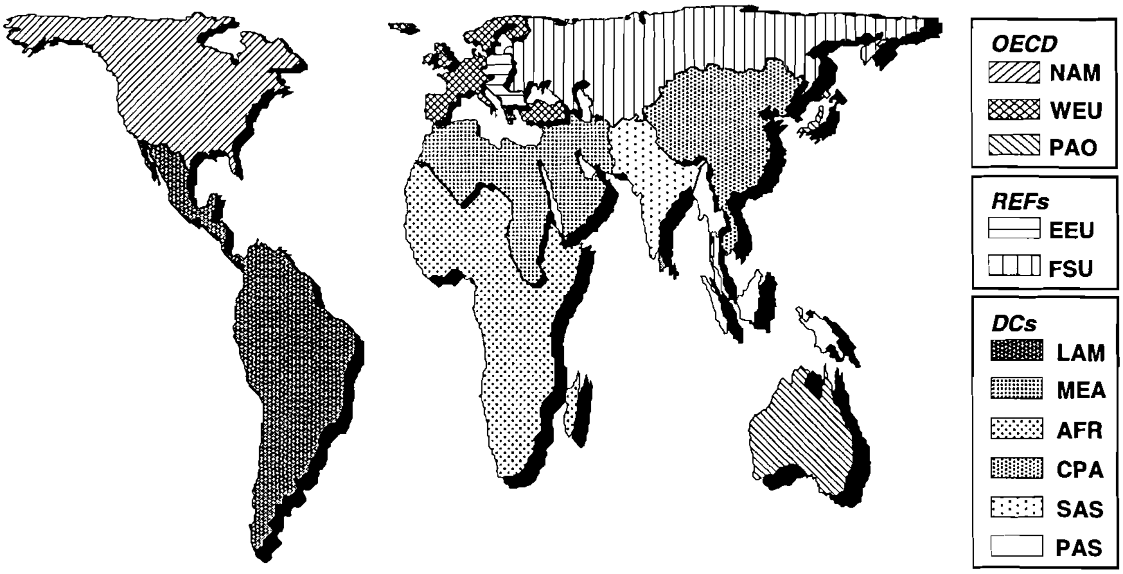
- world population grows in line with current medium projections by the World Bank, United Nations, and IIASA to about 10 billion in 2050 and approaching 12 billion in 2100. It was felt that no useful purpose would be served in using high and low projection alternatives, particularly as these alternatives would divert attention from the main – energy oriented – thrust of the study. The World Bank's estimates have therefore been used;
- the world is divided into 11 regions (Figure 1), defined on the basis of geographical proximity, and similarity of economic and energy systems patterns. Most of the results are reported for three "macro-regions": the transitional economies of the Former Soviet Union and Central and Eastern Europe (labelled REFs); the current developing countries (DCs); and the industrialised countries of the Organisation of Economic Co-operation and Development (OECD);
- social and economic development is substantial, particularly in "the South". During the next century, the current distinction between "developing" "and developed" countries will become inappropriate as affluence increases throughout the world;
- energy efficiency improvements are steady and considerable, but not too far out of line with historic experience. Evidence of the past decade suggests modest expectations are justified until proven otherwise;
- the quantity and quality of energy services grows steadily as the drive for cleaner and more convenient fuels continues;
- formal top-down and bottom-up models have been used to check for internal consistency of the scenarios.

The differences between the cases and their scenarios may be summarised as follows:

Case A – High Growth

Case A assumes high rates of economic growth and technological progress, a liberal international trading regime and preference for markets rather than detailed regulation. Economic growth is some 2% per annum in OECD countries, and double that figure in developing countries. This relatively high growth facilitates rapid turnover of capital stock and shifts in economic structures which promote efficiency improvements and technological advance. Towards the end of the 21st century, average global per capita income in Case A would surpass the highest national levels observed today, indicating that current categorisations between "developed" and "developing" regions will become obsolete.

As indicated, Case A is three pronged with respect to possible alternative energy systems developments:



1 NAM North America
2 LAM Latin America & the Caribbean
3 WEU Western Europe
4 EEU Central & Eastern Europe
5 FSU Former Soviet Union
6 MEA Middle East & North Africa
7 AFR Sub-Saharan Africa
8 CPA Centrally Planned Asia & China
9 SAS South Asia
10 PAS Other Pacific Asia
11 PAO Pacific OECD

Figure 1: IIASA and WEC study 11 world regions.

- *A1* labelled "clean fossils" favors neither coal nor nuclear, but as a result of technological change sees the tapping of the vast potential of conventional and unconventional oil and gas resources. As a result, fossil fuel resources are sufficient to allow a smooth transition to alternative supply sources based on acceptable nuclear and new renewables, matched with high quality energy carriers in the form of electricity, liquids, gas and – later – hydrogen. Coal is regarded as a relatively unattractive "backstop" fossil fuel and continuously loses market share.

- *A2* is labelled "dirty fossils". For a variety of reasons concerns about potential climate change wither away, and coal's vast resources make it the fossil fuel of choice as conventional oil and gas resources dwindle. Local and regional sulphur and nitrogen emissions are controlled through add-on technologies, however challenges continue as coal is exploited at ever deeper and more remote locations, and conversion to synliquids is increasingly required.

- *A3* is labelled "bio-nuc". Large-scale renewables and a new generation of nuclear power lead to a technology-driven transition to a post-fossil fuel age. The transition parallels that which occurred historically as industrialised countries moved from fuelwood through coal to oil and natural gas. In this scenario, natural gas is the transitional fossil fuel of choice, supported by economically competitive oil resources. There is little pressure to exploit non-conventional oil resources or large volumes of coal. By 2100 there is almost equal reliance on nuclear energy, natural gas, modern biomass, and a fourth category composed mostly of solar energy with smaller contributions from wind, geothermal, and a few ocean/tidal schemes.

Case B – Middle Course

Case B is a single scenario, with more modest assumptions about economic growth, technological development, removal of trade barriers, and satisfaction of the development aspirations of the South than in Case A. Recent setbacks and slower economic restructuring than anticipated for the transitional economies, together with weak economic performance in sub-Saharan Africa and some other developing countries, are also reflected in the comparatively modest near-term economic growth assumptions of Case B.

This case has the greatest reliance on fossil fuels of any scenario except the coal-intensive Scenario A2. Beyond 2020 the failure to match depleting fossil fuel resources with the necessary technological advances and exploration and production effort creates challenges for energy supply structures. There is pressure to move into costlier categories of unconventional resources and more remote conventional resources of fossil fuels; financial and environmental constraints loom increasingly large.

This scenario may be seen as more "realistic", or a case of "muddling through".

Case C – Ecologically Driven

Case C is the most ambitious by being highly optimistic about technology diffusion and geopolitical innovations to meet the challenges of the environment and international equity. Substantial resource transfers from North to South recycle environmental taxes to spur growth in the South enabling wide participation in international environmental agreements and policies to reduce emissions from energy supply and end use. Globally, economic growth falls short of Case A but slightly surpasses that of Case B, allowing a substantial reduction in economic disparities.

Case C incorporates policies which reduce carbon emissions to 2 GtC (gigatonnes carbon) by the end of the 21st century. These can either be achieved through economic instruments or effective command and control measures. Model checks confirm that the latter could create inefficiencies. It is believed that incentives rather than taxes – carrots rather than sticks – are more likely to get organisations and individuals to respond positively and quickly.

In Case C nuclear energy is at a cross-roads illustrated by two scenarios. Scenario C1 assumes nuclear is a transient technology that is phased out entirely in the long term, leaving new renewable forms of energy to substitute for fossil fuels. Scenario C2 assumes a new generation of small-scale (200 to 400 MW) nuclear reactors is developed which is, and is also perceived to be, inherently safe.

Each of these six scenarios covers the energy system as a whole from resource extraction to the provision of energy services. They are not simply energy supply or energy demand scenarios.

KEY UNDERLYING ELEMENTS

This summary paper cannot reproduce the richness of detail contained in the full study [1], but five salient elements are summarized here:

- population prospects;

- economic growth;
- energy intensity;
- technological advance; and
- the energy resource base.

To the industrialisation process, which continues in many countries, have been added four further structural transformations:

- urbanisation;
- the transition from non-commercial to commercial forms of energy;
- more convenient, cleaner and flexible forms of energy – essentially increased "quality"; and
- decreasing energy intensity (the specific energy needs per unit of economic activity decline with economic development).

These transformations began in the most developed parts of the world, and have spread globally, but there remain significant differences between regions. Such structural shifts are generally least advanced in developing countries where population is expected to grow rapidly in future.

POPULATION PROSPECTS

A single medium projection of the world's population was assumed in the study (Figure 2) [3]. World population is expected to double in 70 years from 1990 to 10.6 billion in 2060. The last doubling took approximately 40 years. That means population growth is slowing, but the absolute increases will be larger than ever before.

Most of this growth will occur in the present developing countries, or the "South". Not only will the energy consumption balance have shifted from North to South, the geopolitical balance may also have shifted in this direction.

The rate of urbanisation will be even faster than the rate of population growth overall. Most of the largest cities of the world will be in the South. Highly urbanised populations have relatively high per capita energy consumption levels (they also have relatively high income levels). In the Ecologically Driven Case C urbanisation is assumed to proceed at a somewhat slower rate than in the other two cases because locally appropriate, small-scale new renewable sources of energy become available to rural communities and slow the urbanisation process.

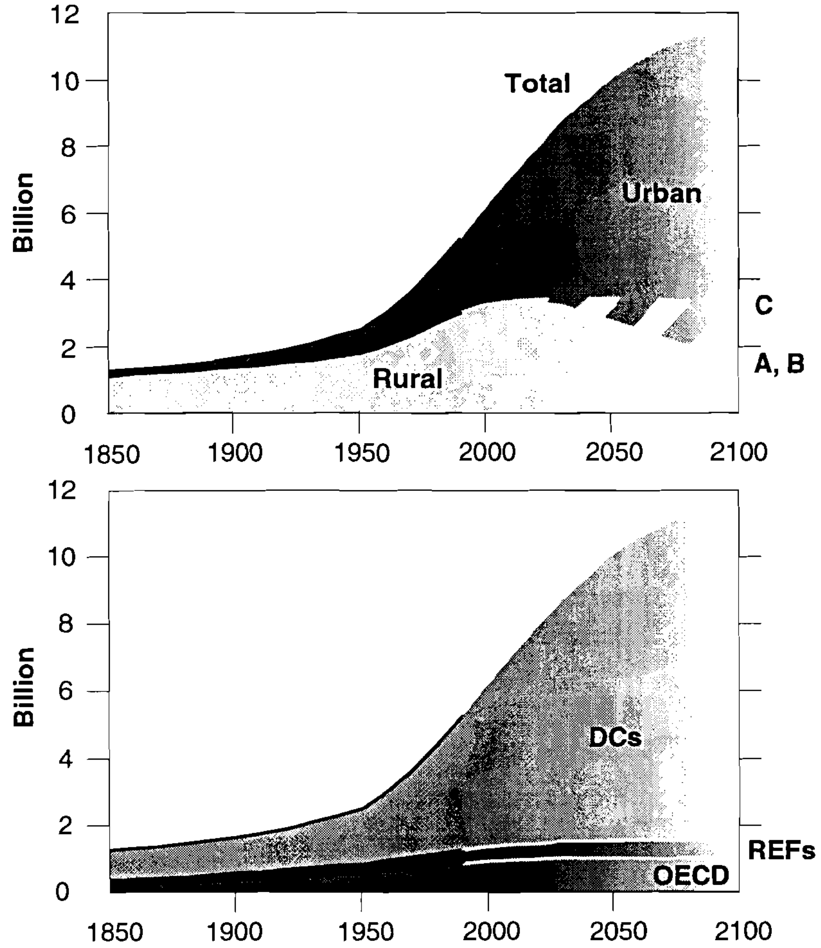


Figure 2: World population, 1850 to 1990, and World Bank projection to 2100 [3], rural-urban (top) and by macroregion (bottom), in billion (10^9) people. Urbanization trends are based on UN [4] and Berry [5].

ECONOMIC GROWTH

The economic growth assumptions to 2050, by case and by region, are given in Table 2, placed in their historical context since 1850. Historical experience indicates both an uneven process across countries and over time, and a certain degree of convergence as less developed economies "catch up" with more developed ones. As a result, the scenarios assume that all countries and regions eventually achieve a "take-off" into accelerated economic development and industrialisation, and conditional convergence in long-term levels of economic development.

The study develops further the calculation of economic growth based not simply on Gross Domestic Product calculated at market exchange rates (GDP_{mer}), but also calculated at purchasing power parities (GDP_{ppp}). Purchasing power parities give a more accurate representation of the relative level of economic activities for economies that do not have a free market for foreign currency exchange. Furthermore it does not assume that domestic prices (e.g., for food in developing countries) are similar to international prices. Use of GDP_{ppp} modifies somewhat the wide disparities in income, wealth and consumption around the world. Under the GDP_{mer}

Table 2: Economic growth rates, historical and 1990 to 2050 (%/yr).

	Historical			Case					
	mer		ppp	1990–2020			2020–2050		
Region	Since 1850	Since 1950	Since 1950	A	B	C	A	B	C
NAM	3.5	3.3	2.1	2.3	2.0	1.7	1.6	1.4	1.1
WEU	2.4	3.7	2.2	2.2	1.9	1.7	1.6	1.3	1.1
PAO	3.9	6.2	3.6	1.9	1.5	1.4	1.2	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	3.6	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	3.2	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	2.8	3.2	2.8	2.6
World	n.a	2.9	2.0	2.7	2.2	2.2	2.6	2.0	2.1

Historical Data Sources: [6, 7].

measure the richest 20% of the world's population produce and consume 80% of the world's product; under the GDP_{ppp} measure the richest 20% consume "only" 60%. The distinction becomes particularly important when considering energy intensity differences among regions.

ENERGY INTENSITY

Energy intensity is a broad aggregate measure, linking energy consumption to units of economic activity. Energy intensities have tended to decline, in the USA and the UK, for instance, for some 125 to 150 years if total energy (non-commercial and commercial energy combined) is taken into account. If only commercial energy is considered, in the USA for example, the decline in energy intensity is postponed – until about 1920. Figure 3 provides historic changes in primary energy intensity for total energy (solid lines) and commercial energy only (dotted lines) for selected countries. For developing and reforming economies both GDP measures (at market exchange rates and at purchasing power parities) are provided. Thus India's total energy intensity has been declining quite sharply based on GDP_{mer}, but remains much higher than the more stable evolution at GDP_{ppp}. Commercial energy intensity, on the other hand, is rising sharply on both GDP measures.

It is assumed in the study that aggregate energy intensities generally improve over time but take account of the impact of commercial energy carriers substituting 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 in industrialised economies. There are, of course, persistent differences between countries and these reflect a range of historical circumstances, development histories, pricing and cultural patterns, including attitudes towards technology. Historically, energy intensity improvements tend to be path dependent, leading

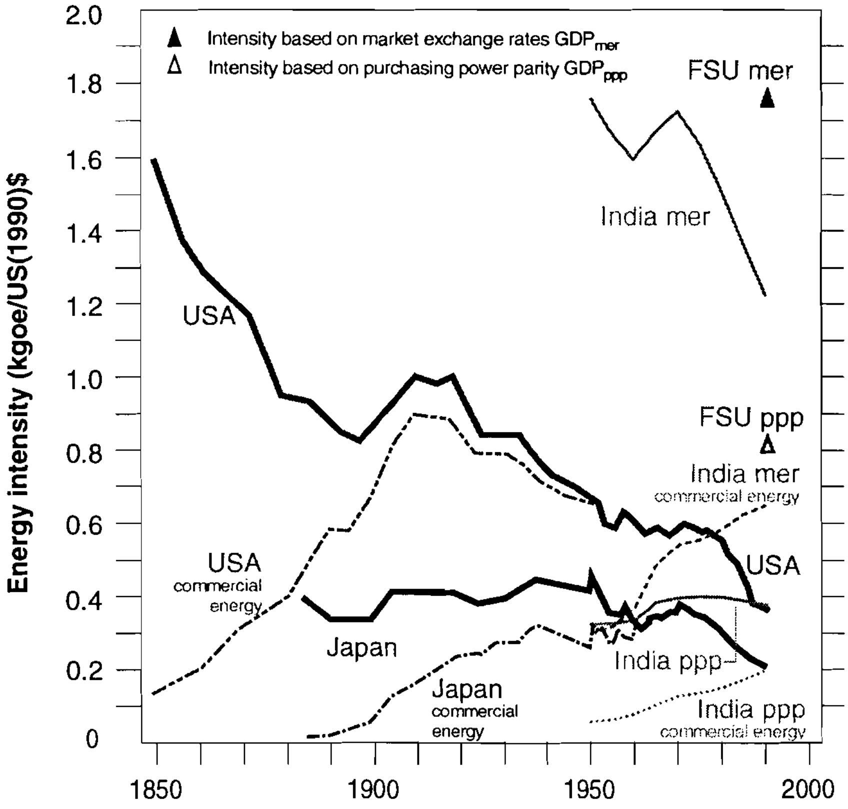


Figure 3: Primary energy intensity for selected countries, total and commercial energy in kgoe per US(1990)$ GDP_{mer} and GDP_{ppp}. Data source: [8, 9, 10]

only to conditional convergence between countries and regions over time, a hypothesis that is also incorporated into the scenarios presented here.

The resulting global energy intensity improvement rates are 1.0% per annum for High Growth Case A, 0.8% per annum for Middle Course Case B, and 1.4% per annum for Economically Driven Case C. Fuller details are given in Tables 3 and 4.

In comparing the energy intensity improvement rates presented here with other studies and earlier WEC cases, important definitional and measurement issues have to be kept in mind. These measurement issues are illustrated below for Case B (Middle Course) for three of our 11 world regions, giving energy intensity improvement rates (percent per year) to 2020 for total primary energy (TPE) and commercial primary energy (CPE), and for market exchange rate GDP_{mer} and purchasing power GDP_{ppp} respectively.

The dynamics of energy intensity improvements change drastically for developing regions as exemplified by Centrally Planned Asia and China and Sub-Saharan Africa. The generally higher energy intensity improvements for Centrally Planned Asia and China are the result of the much higher short-term economic growth rates for Centrally Planned Asia and China than Sub-Saharan Africa; higher GDP growth leading to faster turnover of capital stock yields faster energy intensity improvements in the scenarios. Thus, the evolution of the total primary energy consumption per GDP_{mer} yields a challenging numerical magnitude of energy intensity

Table 3: Three scenarios of energy intensity improvements (primary energy per GDP$_{mer}$, %/yr).

	Case				
	A	B	C	B1 - C[a]	
	1990–2050	1990–2050	1990–2050	1990–2020	
OECD	-1.2	-1.1	-2.0	-1.9	-2.8[a]
REFs	-2.1	-1.7	-2.2	-1.2	-2.7[a]
DCs	-1.6	-1.2	-1.9	-0.8	-2.1[a]
World	-1.0	-0.8	-1.4	-1.3	-2.4[a]

[a] Range of WEC Commission's Report on *Energy for Tomorrow's World* [2]. Improvement rates not directly comparable as based on purchasing power parity (ppp). It should be emphasized that the WEC Commission specifically rejected adoption of any "business-as-usual" cases, and noted that in recent years groups of industrialized countries have achieved overall energy intensity reductions exceeding 1.5% per year (e.g., the European Union since 1974) and exceeding 2.5% per year if road transportation is excluded. But what can be achieved by a few countries over a relatively short period, and what can be achieved by many over a long period, may be two very different things.

Table 4: Energy intensity improvements 1990–2020 for three regions (%/yr).

Region	TPE/GDP$_{mer}$	TPE/GDP$_{ppp}$	CPE/GDP$_{mer}$	CPE/GDP$_{ppp}$
NAM	-1.2	-1.3	-1.2	-1.3
CPA	-2.2	-0.7	-1.5	0.0
SAS	-1.0	-0.3	0.2	0.8

TPE - Total primary energy
CPE - Commercial primary energy
[a] NAM – North America
[b] CPA – Centrally Planned Asia and China
[c] SAS – South Asia

improvements. Conversely, commercial energy intensity measured per GPD$_{ppp}$ assume positive values, i.e., commercial energy consumption grows at least as fast as GDP$_{ppp}$ in Case B.

TECHNOLOGICAL ADVANCE

The full report [1] devotes considerable space to the dynamics of technical progress and to technological innovation and diffusion drawing on IIASA's data bank of 1,400 technologies. Technological change, together with economic structural change, is an important driving force for the evolution of energy intensity.

The three cases assume different rates of technological progress and learning, and the varying impact of related features such as the relevance of international trade requirements for some technologies and the scope for local development and manufacture of others. In all cases, energy options which are not technically feasible today are excluded. Nuclear fusion, for example, is excluded. Hydrogen as an energy carrier is included, because it can be produced with current technologies though not at current commercial costs.

In Case A (High Growth) there is substantial advance in all new energy production, conversion and end-use technologies. These advances are demonstrated across the board: for hydrocarbon

Table 5: Global fossil and nuclear energy reserves, resources and occurrences, in Gtoe.

	Consumption				Resource	Additional
	1850–1990	1990	Reserves	Resources[a]	base[b]	occurrences
Oil						
Conventional	90	3.2	150	145	295	
Unconventional	–	–	193	332	525	1,900
Natural gas						
Conventional	41	1.7	141	279	420	
Unconventional	–	–	192	258	450	400
Hydrates	–	–	–	–	–	18,700
Coal	125	2.2	606	2,794	3,400	3,000
Total[c]	256	7.0	1,282	3,808	5,090	24,000
Uranium	17	0.5	57	203	260	150
in FBRs[d]	–	–	3,390	12,150	15,550	8,900

Source: [1]

– negligible amounts; blanks, data not available.

[a] Resources to be discovered or developed to reserves.

[b] Resource base is the sum of reserves and resources.

[c] All totals have been rounded.

[d] Fast breeder reactors.

exploration and extraction; nuclear electricity generation and hydrogen; renewable sources of electricity generation and biofuel production and conversion; and for advanced end-use conversion technologies such as fuel cells.

In Case B (Middle Course) the advances are less substantial than in Case A, reflecting less concerted research, development and diffusion efforts. In Case B technological change largely focuses on incremental improvements of existing technologies.

Case C (Ecologically Driven) strongly favours low-carbon fossil and renewable energy supply and high efficiency end-use technologies. Technologies in these sectors benefit from improvements rates equal to those in Case A. Technological developments in other energy sectors develop more slowly, as in Case B.

THE ENERGY RESOURCE BASE

The resource base used for the study includes all potentially recoverable coal, conventional oil and natural gas, unconventional oil (shale, tar sands and heavy crudes), and unconventional natural gas (gas in Devonian shale, tight sand formations, geopressurised aquifers and coal seams). Quantities not considered potentially recoverable are classified as "additional occurrences", and are excluded from the resource base. Hence they are not taken into account in the cases/scenarios presented here. The quantities of such occurrences as methane hydrates in tundra regions and in the sea, and natural uranium dissolved in sea water, are huge. Table 5 provides the details.

Numerous sources have been drawn upon in building up Table 5, including IIASA and WEC, which are acknowledged in the full study [1].

The availability of the fossil fuel and uranium resource base varies across the cases and scenarios. It ranges from optimistic in Case A (Scenarios A1 and A3), through cautious (Scenario A2 and Case B), to conservative (Case C). As mentioned above, none of the scenarios assume any "additional occurrences" are brought on stream, but they do indicate the hypothetical availability of enormous quantities.

The fossil fuel resource figures given in Table 5 are certainly sufficient for more than 100 years, even in the highest Case A scenarios. This is not to suggest that temporary or structural energy shortages cannot occur, simply there are no basic geological constraints. There are likely to be other barriers to using such large quantities of fossil energy: technical, financial and environmental. For instance, cumulative carbon emissions of the full exploitation of fossil resources would correspond to 6 to 7-times the current atmospheric CO_2 concentration, which now approaches 360 ppmv (parts per million by volume). Local environmental impacts could also be chronic in many parts of the world (see discussion below).

The use of uranium in the future will depend in part upon the resolution of current controversies surrounding operational safety, waste disposal and proliferation; and in part on the successful development of new technologies.

Renewable energy resources (with the exception of a few hydropower sites) offer much lower energy densities than the fossil fuels. They are limited, therefore, not by the magnitude of their energy flows (that are huge by any standards) but by how these flows can be harnessed and converted to fuels to provide energy services. This implies not only appropriate technology and finance, but also the resolution of potential local environmental impacts.

Nevertheless, it is also a fact that the Earth annually intercepts about 130,000 Gtoe (gigatonnes oil equivalent) of solar energy compared with current total global energy consumption of about 9 Gtoe. This is one reason why it is not unlikely that, in the long run, the more direct uses of solar energy from photovoltaics to solar thermal will account for the major part of renewable energy. A second reason is that other forms of renewable energy may either have unacceptable local environmental impacts when pursued on a large scale (plantation biomass) or when pursued in particular locations (beautiful landscapes, sensitive estuaries, rare natural habitats).

The key issue, therefore, is what fraction of renewable energy flows can and will be harnessed for the energy purposes of future generations of people. The WEC's reports *Energy for Tomorrow's World* [2] and *New Renewable Energy Resources: A Guide to the Future* [11], identified renewable energy potentials by the year 2100 of up to 13 Gtoe, of which 10 Gtoe could be supplied by "new" renewables – modern biomass, solar, wind, geothermal, ocean/tidal, and small hydropower (under 10 MW).

Progress towards that longer-term potential is, however, likely to be slow - particularly with current policies. Major, effective and internationally coordinated policy support would be required if developments are to be accelerated over the next two or three decades. In the longer term, nevertheless, the potentials for renewables increase significantly as technology and both absolute and relative cost improvements takes place in the scenarios.

PROSPECTS FOR ENERGY SYSTEMS

The energy system is service driven from the bottom-up, while energy flows are resource and conversion process driven from the top-down. Energy flows from energy sources to end-use, and driving forces from population growth to technological change, interact intimately. In the study, therefore, the dichotomy between supply and demand has been replaced with the broader perspective foreshadowed in the WEC's report *Energy for Tomorrow's World*: "... the energy community is the captive of its own technology in continuing to use these distinctive terms in ways which fail to recognise them as elements of ... a system which should be driven not by the exigencies of primary energy supply, trade or the energy market but by the end-point services which energy is the means of providing" [2 p. 246]. The scenarios here are therefore described in terms of primary and final energy consumption. Primary energy depicts the structure of energy extraction and conversion, while final energy shows the structure of energy end-use.

The six scenarios are intended to illustrate the possibilities arising out of steps taken to develop new energy technologies, energy resources and financial institutions over a time period, guided by policy and end-use objectives which permit a range of outcomes. There is also time to achieve capital turnover and fundamental change in the energy system. By 2020, many current energy end-use devices will have been replaced by those just being introduced for commercial use today or those on the near horizon – new vehicles, industrial processes and heating systems, and parts of the housing stock and infrastructures. Many power plants will have been replaced, and others will be nearing the end of their useful lifetimes. The time horizon to 2050 and on to 2100 means that all energy technologies and devices are likely to have been replaced at least twice, and most energy infrastructures as well. Such turnover offers enormous new supply and end-use opportunities reflected in the scenarios of the study.

PRIMARY ENERGY

Figure 4 illustrates world primary energy use and world population growth from 1850 to the present time, together with the six scenarios grouped into three cases, labelled A, B, and C. Primary energy requirements of the scenarios within each case are almost identical (see Table 6).

The three cases indicate that global primary energy use would increase up to 3-fold by 2050, and 2 to 5-fold by 2100. Case A (High Growth) portrays primary energy growth rates approaching those of the historical experience since 1850, while Cases B (Middle Course) and C (Ecologically Driven) present substantially lower growth. Case C in particular represents a radical change, with emphasis on energy efficiency and conservation that results in a clear decoupling of energy and economic growth.

The current developing countries account for the overwhelming proportion of the increase in global primary energy requirements. Energy demands increase modestly in the industrialised North in Case A, grow marginally in Case B, and actually decline in Case C.

Table 6 sets out the basic figures by 2050 for primary energy supply and demand, the fuel mix, and final energy demand of the six scenarios. Investment and emissions implications are also provided, topics dealt with below in this paper.

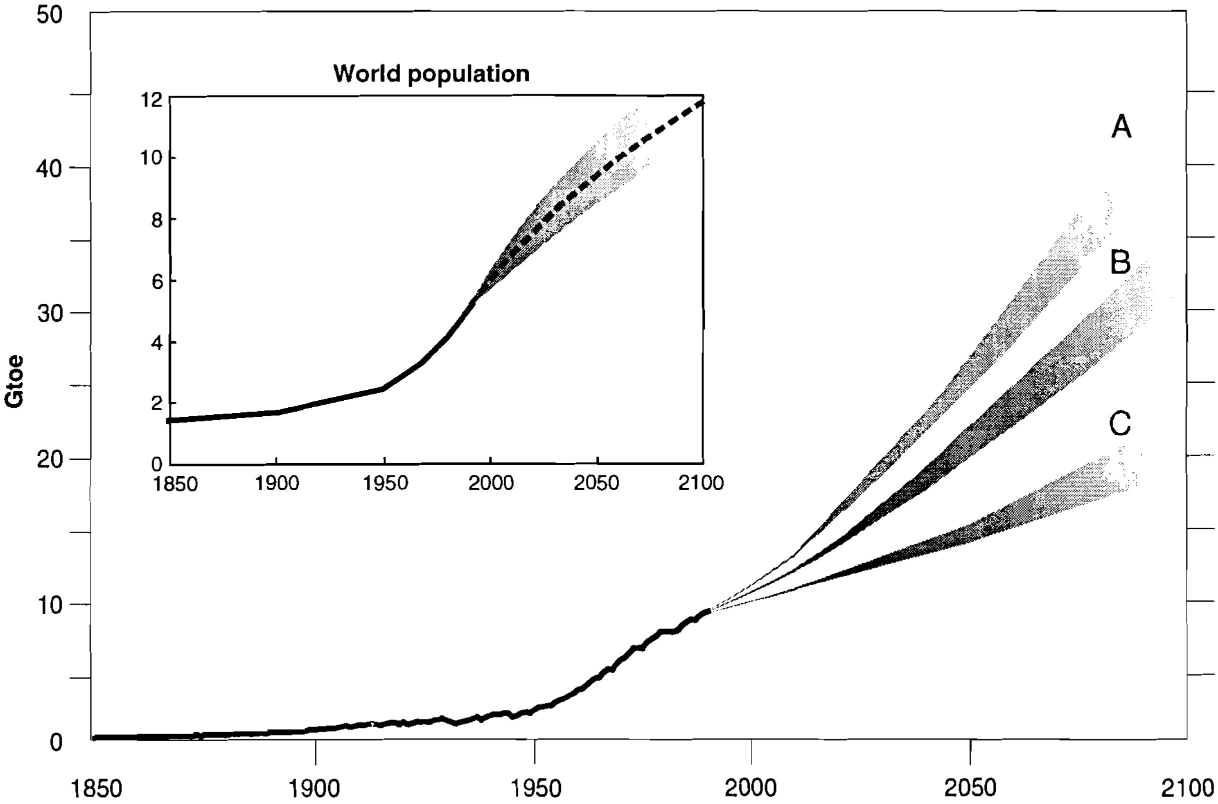


Figure 4: Global primary energy use (Gtoe), 1850 to present, and in the three cases to 2100. The insert shows global population growth, 1850 to present, and its projection [3] to 2100, in billions (10^9) of people.

Figures 5 and 6 show the changing primary energy mix of the six scenarios. Figure 7 provides the cumulative fossil fuel requirements, 1990 to 2050 for the six scenarios. Figure 8 shows the converging structure of final energy use of the cases/scenarios.

Common to all six scenarios is that the peak of the fossil era has passed. Fossil fuel consumption will grow more slowly than total primary energy needs. Even in Case A, Scenarios A1 and A2, the share of fossil energy declines after 2020. The two most important transitional fuels – oil and natural gas – face declining shares during the next century. In absolute volumes, however, requirements increase considerably compared to current levels.

The scenarios suggest that the world may now only be one-third of the way through the oil age; and one-fifth through the natural gas age. Even the low coal Case C scenarios suggest that as much coal will be used between 1990 and 2050 as was used between 1850 and 1990. Views that these energy scenarios threaten the immediate or early demise of oil, gas or coal are therefore seriously misplaced.

The three variants of the high growth Case A result in between 1,300 and 2,000 Gtoe of fossil energy being consumed by 2100 of which oil and gas comprise 900 to 1,200 Gtoe. This relates to the 1,300 Gtoe fossil reserves figure given in Table 5 and to a fossil resources figure of some 3,800 Gtoe.

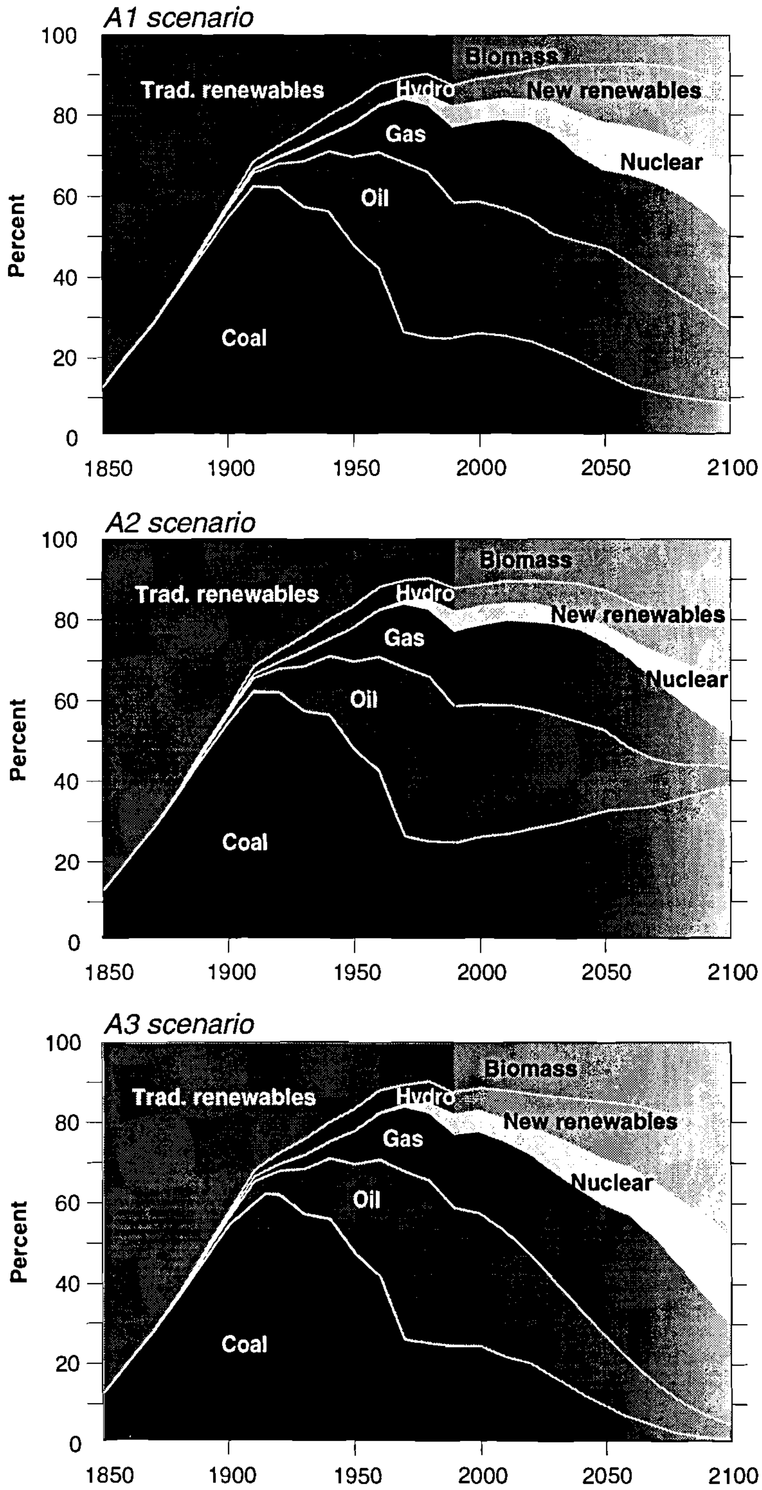


Figure 5: Evolution of primary energy shares, 1850 to 2100, for Case A: A1 Scenario, the coal-intensive A2 Scenario, and the "bio-nuc" A3 Scenario.

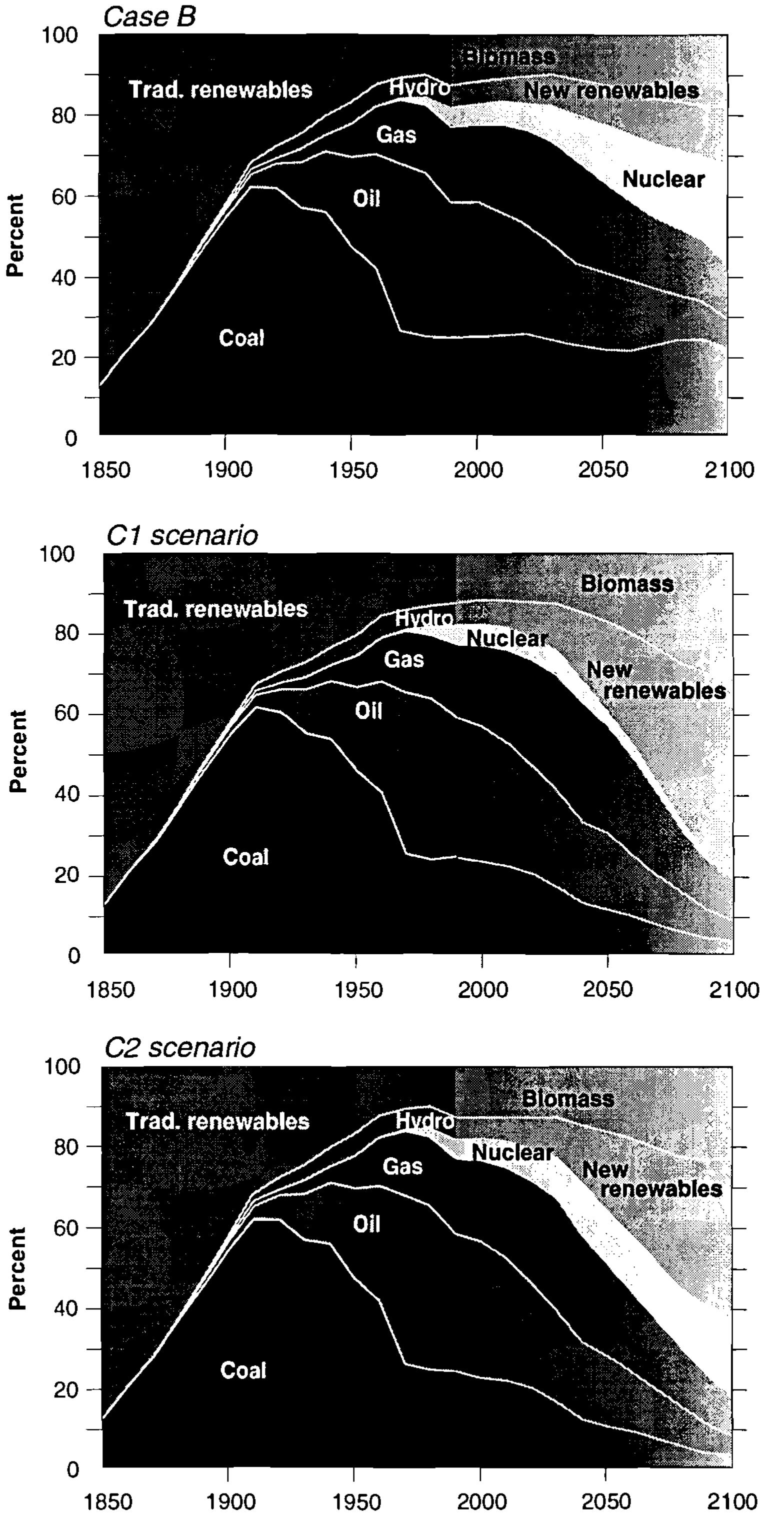


Figure 6: Evolution of Primary Energy Shares, 1850 to 2100, for Cases B, C1 ("nuclear phase-out"), and C2 ("bio-nuc").

Table 6: Characteristics of three cases and their six scenarios for the world in 2050.

	Case					
	A			B	C	
	A1	A2	A3		C1	C2
Primary energy, in Gtoe	25	25	25	20	14	14
Primary energy mix, %						
Coal	24	32	9	21	11	10
Oil	30	19	18	20	19	18
Gas	24	22	32	23	27	24
Nuclear	6	4	11	14	4	12
Renewables	16	23	30	22	39	36
Resource use 1990–2050, in Gtoe						
Coal	235	324	180	226	143	141
Oil	323	302	284	257	210	210
Gas	241	247	285	227	210	197
Energy sector investment US$ 10^{12}	1.2	1.7	1.2	1.1	0.7	0.7
US$/toe supplied	50	67	47	56	50	50
as % of GWP[a]	1.2	1.7	1.2	1.5	0.9	0.9
Final energy, in Gtoe	17	17	17	14	10	10
Final energy mix, %						
Solids	16	19	18	23	19	20
Liquids	42	36	33	33	34	34
Electricity	17	18	18	16	18	17
Other [b]	25	27	31	28	29	29
Emissions						
Sulfur[c,d], MtS	23	86	15	35	4	3
Nitrogen[d], MtN	21	55	21	22	14	12
Carbon, GtC	12	15	9	10	5	5

[a] Gross World Product

[b] District heat, gas, and hydrogen.

[c] Unabated sulfur emissions in Case A could be three (A1) to five (A2) times higher leading to unacceptable local and regional environmental impacts.

[d] Preliminary global estimates.

In all scenarios there is also a significant expansion of renewables, but the driving forces vary. Case B represents the most cautious assessment of renewables' prospects. Over the longer-term, however, renewables expand at a steady pace in all scenarios. Even in Case B renewables contribute 22% (4.4 Gtoe) of world primary energy consumption by 2050, and 33% (11 Gtoe) by 2100. In Case C and Scenario A3, renewables reach as much as 22 Gtoe by 2100, with biomass assumed to contribute over 8 Gtoe which raises doubts about its viability due to competing land uses and local environmental impacts, as well as the competitiveness of other energy sources. These issues are discussed in more detail in the full report of the study [1].

Scenario A3 also requires up to 75 new nuclear reactors per year to 2050, which implies that public opinion has become convinced of the safety and general acceptability of nuclear power generation. In Scenario C2, nuclear power grows to a market share of 12% worldwide by 2050

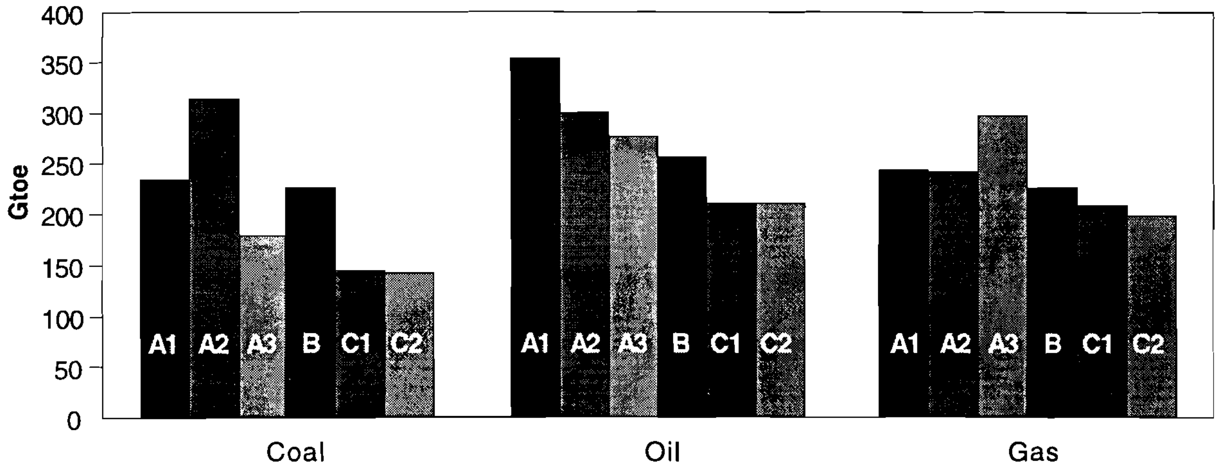


Figure 7: Cumulative fossil energy requirements, 1990 to 2050, in Gtoe.

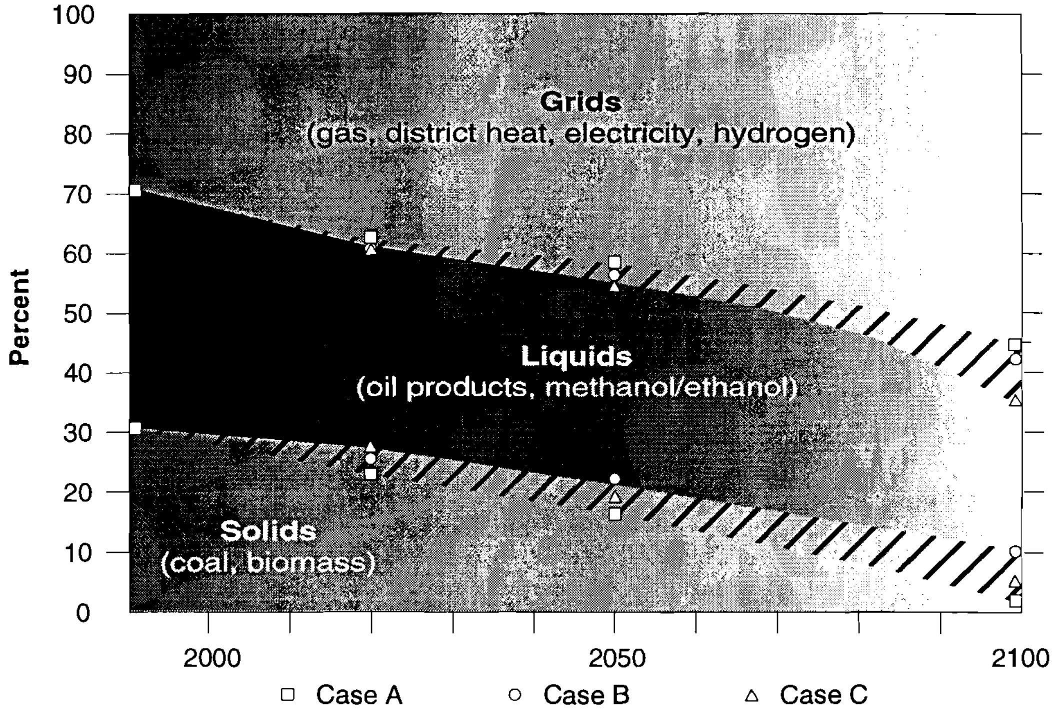


Figure 8: World supply of final energy by form: solids (coal and biomass), liquids (oil products and methanol/ethanol), and grids (gas, district heat, electricity, and hydrogen). Overlapping shaded areas indicate variations across Cases A, B, and C.

and 19% by 2100 on the basis of new, small-scale, decentralised technologies. In the absence of radical improvements in public acceptability, technology and economics, nuclear energy might prove a transient technology, as illustrated in Scenario C1.

Relatively rapid and substantial technological change accompanies the comparatively high economic growth and energy requirements of the Case A scenarios. Scenario A1 assumes that this technological change permits the utilisation of large volumes of both conventional and non-conventional oil and gas resources, higher energy efficiency, and mitigation of most environmental impacts. Fossil fuels still account for about 50% of primary energy consumption in the year 2100. Scenario A2 is more conservative about technological change and resource availability, the main explanation for why this scenario is more coal intensive. Scenario A3 is "technology intensive", but here new renewable energy sources and new nuclear technologies combine to permit the transition to a post-fossil age. By 2100 in Scenario A3, fossil fuels account for 30% of world primary energy consumption; almost all of this is supplied by natural gas.

The single scenario Case B (Middle Course) is more cautious in respect of economic growth, energy availability and technological change. Fossil fuels still account for about 45% of world primary energy consumption in 2100 but unless rather dramatic changes occur to bring in new fossil fuel discoveries or the rapid expansion of non-fossil energy sources then resource scarcities become likely. Financing and environmental constraints are likely to be particularly severe in this case as more remote and dirty fossil fuel resources need to be exploited and converted to synfuels on a large scale.

The (Ecologically Driven) Case C scenarios offer the greatest challenges, but also opportunities, as the emphasis shifts to accelerating energy efficiency, encouraging energy conservation wherever appropriate, and promoting new, decentralised and environmentally benign technologies. In addition to the vigorous control of local and regional pollutants, a global regime to control the emissions of greenhouse gases is established. The goal is to reduce anthropogenic CO_2 emission levels to 2 GtC by 2100 (corresponding to one-third their current level). This is anticipated to lead to eventual stabilization of atmospheric CO_2 concentrations.

Case C outlines pathways for achieving the transition from the current dominance of fossil fuels to the dominance of renewable energy flows. By 2050 renewables account for 40% of world energy consumption, a share that increases to over 80% by 2100. Efficiency and environmental criteria require a high quality of energy carriers delivered to end-users. Renewable energy sources are therefore transformed into electricity, liquid and gaseous energy carriers. Fossil fuels are transitional fuels of rapidly diminishing significance. Nuclear energy is at a cross-roads in Case C, with new nuclear energy staging something of a revival in Scenario C2. In Scenario C1 nuclear energy is a transient technology that becomes virtually phased out by 2100.

All of the scenarios illustrate an expected drive by consumers for more flexible, more convenient and cleaner final energy forms.

FINAL ENERGY

Electricity is already an important energy carrier, and its contribution increases in all six scenarios. Methanol is also expected to play a larger role in the future. Hydrogen is another energy carrier expected – eventually – to play a significant role, but mainly post-2050 as considerable time is required to improve its economics and build-up a hydrogen infrastructure. Overall, the pattern of final energy use is remarkably consistent – and converging – across all scenarios.

The most obvious shift is from energy used in its original form – whether traditional biomass or coal, etc., – to elaborate systems of energy conversion and delivery. Energy delivered by pipelines and networks plays an increasing role.

There are some important implications for energy efficiency in these shifts, and challenges to traditional conventions and definitions. Hydropower for instance, is converted into electricity at actual efficiencies approaching 90% but a standard convention bases the conversion efficiency on the amount of fossil fuel that would have been required to produce the same amount of electricity – the "substitution method". This reduces hydropower efficiency to an average of 38.5%, a definition used by the WEC [2] for all non-fossil sources of electricity. The more elaborate energy conversion systems become the more significant this difference is. The conventional accounting approach has been used in the study, but produces relatively low results with strong implications for renewable energy (photovoltaic efficiency is reduced to 18% if solar is considered a primary energy input, wind energy becomes even more problematic).

FINANCIAL AND ENVIRONMENTAL IMPLICATIONS

Financing

The financing requirements of the energy prospects given in all three cases are clearly enormous. The problems of financing energy development are already of great concern in many developing countries. The growing difficulties in accessing official financial assistance from multilateral bodies, institutional barriers, inappropriate pricing policies and poor investment returns all give cause for concern. Nevertheless, 3 to 4% of GDP is invested in the energy sectors, a ratio which is expected to remain fairly stable; and savings rates are about 24% on average in developing countries and 20% in transitional economies. Therefore, provided the necessary institutional and pricing adjustments are made, and returns on investment become sufficiently attractive, there seems no fundamental reason why the finance for energy investments should not be forthcoming.

The availability of international financing will also be affected by how the international trading regime develops. Case A (High Growth) assumes a strong drive towards free trade; Case B (Middle Course) incorporates continuing trade barriers, but none which greatly affect energy trade; and Case C (Ecologically Driven) makes international trade conditional on satisfaction of sustainable development objectives and whether projects and technologies satisfy the emerging environmental standards. In Case A, therefore, financing is attracted to where there is political stability, relatively high returns on investment and attractive growth prospects, regardless of the nature of political regimes. Political considerations and regional bloc trading regimes have their greatest influence in Case B. Financing of approved technologies and environmentally-sound energy sources and schemes is not a problem in Case C, but other investments would be heavily regulated.

Table 7 provides the study's estimate for cumulative investments in energy supply and conversion by region and by scenario, for the period 1990–2020 and 2020–2050.

These estimates, by convention, include capital for production capacity, for transmission and distribution infrastructures, and for complying with environmental standards. They do not include investments in end-use technologies, which are traditionally counted as durable consumer goods or business investments. However, the fact that the performance of end-use technologies plays such an important role in all cases and scenarios in the study, suggests the need for a new approach in evaluating energy sector investments. Integrated resource planning, for exam-

Table 7: Cumulative investments in energy supply by region, 1990–2020 and 2020–2050.

Energy investments	Case A[a] 1990–2020	Case A[a] 2020–2050	Case B 1990–2020	Case B 2020–2050	Case C[b] 1990–2020	Case C[b] 2020–2050
Cumulative in trillion US$(1990)						
OECD	8	10	7	10	5	4
REFs	3	6	2	5	2	3
DCs	9	18	7	15	6	11
World	20	34	16	30	13	18
As share of GDP (in percent)						
OECD	1.1	0.8	1.1	0.9	0.7	0.4
REFs	9.0	4.3	7.9	5.9	7.0	3.9
DCs	3.7	2.3	3.6	2.8	2.9	1.8
World	1.9	1.6	1.8	1.7	1.5	1.1
Per unit of primary energy US$(1990)/toe						
OECD	50	49	51	60	46	42
REFs	56	53	67	74	54	63
DCs	44	49	40	51	42	48
World	48	49	48	56	45	49

[a] A1 scenario; [b] C1 scenario.

ple, has begun to extend the traditional energy perspective to take into account investments in end-use technologies.

Between 2020 and 2050, capital requirements grow substantially in absolute terms, but still more slowly than GDP in all scenarios. There is a shift from supply-side investments (included in Table 7) to end-use technology and infrastructure investments (which are excluded). If the latter had been included in the table the numbers are likely to have been greater by at least 50%. There are also advances along the technological learning curve and continued improvements in energy intensity which are reflected in the figures of the study (and which tend to reduce future investment needs markedly).

The results given in Table 7 indicate a range of cumulative capital requirements between 1990 and 2020 of US$13 to 20×10^{12} ($1990). For comparison, the latter figure equals the world GDP of the year 1990. The developing region's share rises sharply from today's 25 to 30% to between 42% and 48%, and becomes the largest energy capital investment market in all three cases. Considering energy investments as a share of "macro-region" GDP, the transitional economies rank the highest with 7 to 9% of regional GDP devoted to energy investments. Obsolete energy structures and slow economic revival are the background. Developing countries invest 3 to 4% of GDP in the energy sector, and the OECD region invests about 1%.

Annual capital requirements rise from under US400\times 10^9$ in 1990 to US500\times 10^9$ – US750\times 10^9$ (US$1990) by 2020, and to US$700 to 1200$\times 10^9$ (US$1990) by 2050. A large share of this investment will still need to be externally financed.

Environmental Impacts

Three kinds of environmental impacts have been considered in the study and are addressed in more detail in the main study report [1]: local impacts of indoor and urban air pollution in developing countries; regional impacts of sulphur and nitrogen emissions and their potential contribution to acidification; and greenhouse gas emissions, particularly CO_2, and their potential contribution to enhanced global warming.

Local Impacts

There are two important categories of local pollution. First, that arising from poverty: such as poor sanitation, polluted water, high levels of indoor air pollution caused by burning traditional fuels - impacting with particular severity on women, children and the elderly – and high concentrations of particulate matter in urban areas. Secondly, pollution of modern origins: resulting from dense motorised traffic and from low-efficiency coal combustion in electricity generating plants, industrial premises and homes. Concentrations of suspended particulate matter, lead, volatile organic compounds, tropospheric ozone and sulphur dioxide widely exceed World Health Organization guidelines, particularly in urban areas.

The study reaches the following conclusions:

- improving conversion efficiencies in end-use devices has a key role to play in conserving traditional resources such as fuelwood and reducing indoor air pollution;
- structural shifts away from traditional energy end-use patterns and energy carriers towards more efficient modern conversion technologies and cleaner energy carriers are urgently necessary;
- there will need to be a long-term shift towards energy services provided through clean, grid-dependent fuels.

Environmental constraints, together with increasing affluence, are expected to lead to a long-term convergence of energy end-use systems and infrastructures in the direction of convenient and clean energy forms across the scenarios presented here, despite diverging energy supply structures. Local solutions to local problems need to come forward, appropriate in nature and scale to local circumstances, until the more long-term structural changes towards clean energy end-use carriers yield noticeable effects on improvements in local environmental quality. There are variations among the scenarios in their environmental impacts, however, Scenario A2 and Case B – both relatively coal intensive – arouse the gravest concern.

Regional Impacts

Energy emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) have both local and regional impacts. Acid deposition is of particular concern.

IIASA's RAINS model [12, 13] was used to calculate unabated scenarios of sulphur deposition in Europe and in South and East Asia. The analysis was carried out for the coal-intensive Scenario A2 and for the Case C scenarios.

In Scenario A2, in the absence of sulphur abatement, sulphur emissions in Europe would increase by approximately 50% over the next 30 years. Sulphur deposition would exceed 16 gS/m^2 per year in large areas of Central, Western and Northern Europe. This contrasts to the requirements of the Second Sulphur Protocol on Transboundary Air Pollution of the United Nations Economic Commission for Europe, which calls for reduction measures to lower maximum excess deposition to below 3 gS/m^2 per year.

In the rapidly growing economies of Asia the situation is even more dramatic. In the unabated Scenario A2, SO_2 emissions in South and East Asia triple by 2020 in the absence of abatement measures. It should be noted that the implications of current national energy projections exceed even this pessimistic scenario.

In the unabated Scenario A2 ambient air quality in South and East Asia deteriorates significantly in both urban and rural areas, with sulphur deposition reaching double the worst levels ever observed in the most polluted areas of Central and Eastern Europe. Deposition exceeds the "critical loads" for most of the ecosystems in the region, where "critical loads" are defined as the maximum deposition levels at which ecosystems can function sustainably. The significance of these findings is that, in the absence of emissions abatement, critical loads for economically important food crops in Asia under Scenario A2 are expected to be exceeded by factors up to 10.

Given these results, the scenarios of the study all incorporate only advanced coal technology, including scrubbers for new electricity generation capacity. Sulphur emissions are therefore significantly lower than in the unabated case. For Case A, European emissions in 2020 are between 13 and 15 million tonnes of SO_2 compared to 30 million tonnes in the unabated case. For Asia, Case A emissions in 2020 range from 25 to 45 million tonnes of SO_2, compared to over 80 million tonnes for the unabated case.

Further emission reductions are feasible, but would require substantial additional investment requirements in the Case A scenarios. For the Case C scenarios, energy demand is much lower due to conservation efforts and much less sulphur-containing fossil fuel is used. This would keep the growth of unabated SO_2 in Asia over the next two decades below a factor of 2. Consequently, less stringent abatement measures are required and could be focused more economically on specific local "hot spots". Overall, sulphur emissions in Case C can be kept at, or slightly below, 1990 levels with control costs under half those required in Scenario A2.

These results indicate that in Asia concerns about sulphur emissions, and their potential regional impacts on food security, will take precedence over global, long-term environmental issues such as potential climate change. Nitrogen emissions are likely to have much the same relative priority.

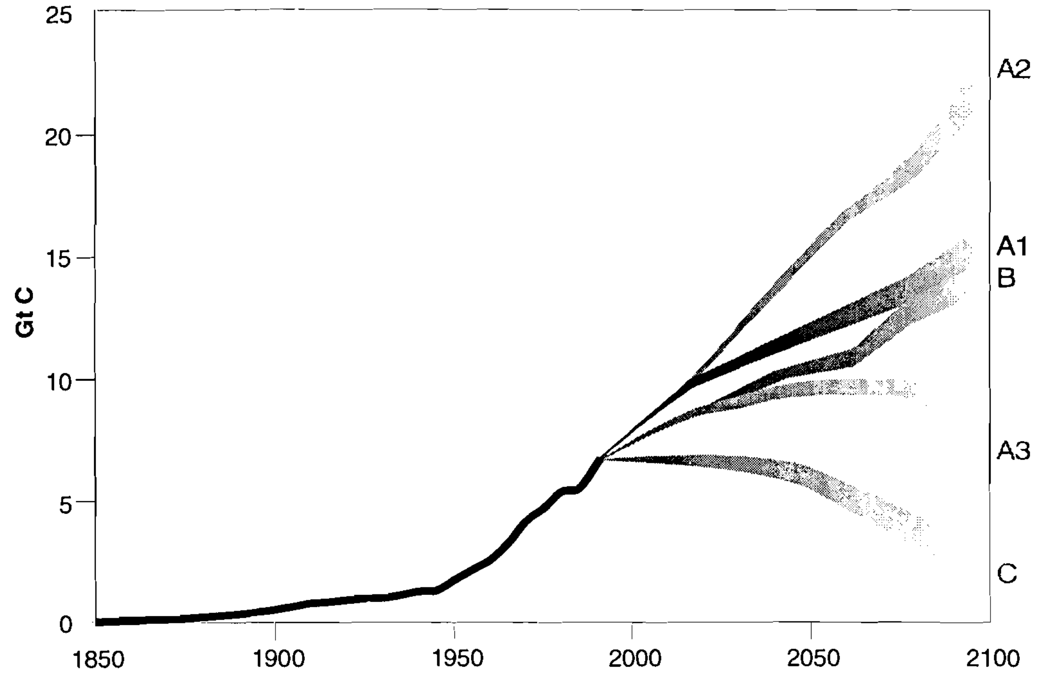


Figure 9: Global energy-related carbon emissions, 1850 to 1990, and for three scenario families to 2100, in GtC.

Greenhouse Gas Emissions

The study concentrated on future CO_2 emissions, as the dominant greenhouse gas, for each of the six scenarios as implied by their level of energy consumption and structure of energy supply. Figure 9 shows the results.

CO_2 emissions vary substantially between the scenarios. In the coal-intensive Scenario A2 they reach 22 GtC (gigatonnes elemental carbon) in 2100, in Scenario A1 15 GtC, but in Scenario A3 significant structural change in the energy system reduces the figure to 7 GtC. The latter is about the same level as current global energy-related carbon emissions, yet the energy consumption would have risen 5-fold. Case B's emissions are comparable to those of Scenario A3 up to 2050, but are nearly double by 2100. The two scenarios of Case C were constrained to stabilise emissions at current levels again by 2050, in order to achieve an emission ceiling of 2 GtC (one-third their current level) by 2100.

The resulting cumulative carbon emissions, considered of particular relevance for potential climate change, from the study are compared in Table 8 to earlier WEC scenarios [2] and to comparable emission scenarios of the IPCC [14, 15].

In contrast to many other scenarios, which combine optimism about high economic growth with pessimism about technological change, resource availability (except for coal production) and efficiency improvements, the scenarios presented here offer a more consistent range of possible futures.

The atmospheric CO_2 concentrations and surface temperature warming that might result from the scenario emissions were calculated using a carbon cycle and climate model developed by Wigley

Table 8: Cumulative emissions 1990–2100 (GtC): IPCC and WEC scenarios compared.[a]

IPCC/IS92 emissions scenarios	a	1,500
	b	1,430
	e	2,190
WEC Cases: "Energy for Tomorrow's World, 1993	A	1,425
	B	1,130
	C	625
IIASA and WEC Cases "Long-Term Energy Perspectives" 1995	A2	1,720
	A1	1,350
	A3	980
	B	1,190
	C1	590
	C2	580

[a] On comparable world population assumptions (UN medium projection).

[16]. Figure 10 provides the results of the model used for atmospheric CO_2 concentration for the six scenarios. By 2100 the two Case C scenarios achieve an atmospheric CO_2 concentration below 420 ppmv (parts per million by volume); Case B is below 580 ppmv; and the three Case A scenarios are below 520 ppmv (A3), 610 ppmv (A1), and 730 ppmv (A2). Thus only Scenario A2 exceeds the IPCC's "preferred" scenario, IS92a.

There are considerable uncertainties surrounding the implications of such concentration increases for temperature change (as indicated for Case B in Figure 10). For the Case C scenarios global mean surface temperature rise at 2100 might be less than 1.5°C from today's level; the Case A scenarios and Case B about +2.0 to +2.5°C.

These results indicate that, if the current state of knowledge about the radiative forcing due to anthropogenic activities is well-founded, the energy sector is indeed a major stake holder. Even in the Case C scenarios the energy sector would account for 40% of all long-term changes in radiative forcing (including agriculture and deforestation). In Scenario A3 the corresponding figure is 50%, and in Scenario A2 80%.

CONCLUSIONS

All six scenarios analyzed in the study outline the following convergent and pervasive developments: increasing demand for energy services together with population growth and economic development; increasing quality and environmental compatibility of final energy forms; a shift in the global balance of economic activity and energy use from North to South; the availability and reliance on fossil fuels for many decades to come.

Technological progress and appropriate investment to match energy sources to the desire for more flexible, convenient and clean forms of energy required to service consumer needs are of crucial importance, but several decades of turnover of capital stock will be required to achieve that match. In the meantime, unless the long-term goal is itself matched by the appropriate policies and investment decisions it will become even harder and more costly to change course.

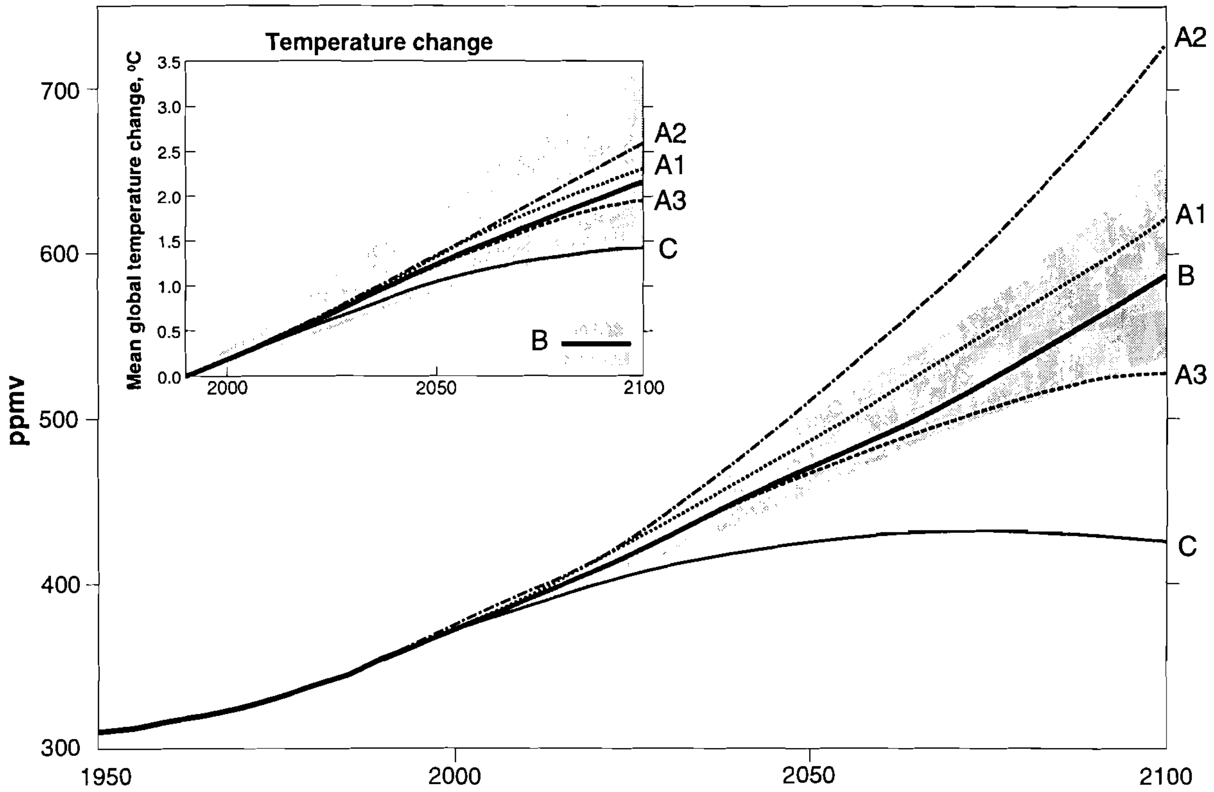


Figure 10: CO_2 concentrations (ppmv), 1950 to 2100, and global mean temperature change (°C), 1990 to 2100. The (substantial) model uncertainties are indicated for Case B.

Investment decisions to 2020 are, therefore, an important concern – and not simply because of the tremendous sums of money involved.

Assumptions made elsewhere, that high energy demand growth and limited technological and financial progress are consistent, are questioned in the study. Strict international environmental policy measures (including limits on CO_2 emissions) and policies to promote international equity (Ecologically Driven – Case C) prove also consistent with substantial economic growth and energy development. Although individual countries or sectors may suffer from constraints, the overall result can be a positive sum game, and potential losses can be reduced or averted by strategies to diversify out of activities in long-run decline.

All scenarios show, for instance, that the international oil and natural gas industries are still far from being half-way through their life cycle in terms of volumes extracted and used; even for coal the most hostile scenarios indicate a prospective lifetime of several decades. Thus all three cases, all six scenarios, reflect substantial growth for all energy industries to at least 2020. The coming decades will see much reshuffling within and among energy sectors. Many new business opportunities will arise linked to cleaner and more convenient fuels, to liquid rather than solid fuels, to grid and other interconnected supplies, and to more locally appropriate – often small scale – energy sources and conversion technologies.

However, the scenarios indicate prospects will diverge after 2020, with different energy industries embarked on often mutually exclusive development paths. Coal, despite its huge resource base, could be particularly threatened – due to increased competition from other energy sources and due to environmental constraints. By contrast the oil industry, and the natural gas industry to an even greater extent, have a long future ahead. New markets will have to be developed for traditional fuels, recognising that the shift from selling energy to marketing energy services will continue and intensify.

The central message across all six scenarios is that energy end-use patterns are converging towards cleaner, more flexible and convenient energy forms, while energy systems structures are diverging as a result of emerging opportunities and the availability of policy choices. Although the structural changes in the near term will be modest, the seeds of long-term changes need to be initiated now. The near term investments embodied in both capital stock and knowledge (research and development, and technology) will shape which of the divergent long-term alternatives will be taken, and which ones will be precluded.

The study has identified patterns that are robust across a purposely broad range of scenarios. It has also identified the conditions under which energy systems structures diverge into alternative directions. But no analysis can ever turn an uncertain future into a sure thing.

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APPENDIX I: METHODOLOGY

Reproducibility of results adds to their validity. This is especially the case when presenting long-term scenarios for which there are no established, rigorous validity proofs. A necessary – though not sufficient – condition for reproducibility is a good description of the methods that produced the results. This appendix presents a summary description of the methods used in the study, and references where more complete descriptions can be found.

The analysis started with two principal exogenous variables: population growth by region, and per capita economic growth by region. Levels of primary and final energy consumption were derived using a model developed at IIASA labeled simply *Scenario Generator* (SG) [17]. It is essentially a combination of an extensive data base of historical data on national economies and their energy systems, and empirically estimated equations of past economic and energy developments.

For each of the scenarios, the SG generated plausible future paths of energy use consistent with historical data and with the specific features that were specified for the scenarios, e.g., high or moderate economic growth, rapid or more gradual energy intensity improvements, technological development across the board, or high development in green technologies and slower development for fossil fuels.

Two other models were then used in an iterative mode for testing for consistency among all the pieces of each scenario. A model of energy-economy interactions called 11R was used to check for consistency between a region's macroeconomic development and its energy use. 11R is a modified version of Global 2100, originally published in 1992 [18], and subsequently used widely in energy studies throughout the world. IIASA's energy supply model called MESSAGE III provided detailed estimates of energy demand and supply [19, 20]. MESSAGE III is a dynamic linear optimization model, calculating cost-minimal supply structures under the constraints of resource availability, the menu of given technologies, and the demand for useful energy. Both models use a discount rate of 5% per annum. The two models are used in tandem because they correspond to the two different perspectives from which energy modelling is usually done: top-down (11R) and bottom-up (MESSAGE III). The model-linking methodology is described in [21].

The regional acidification impacts were calculated using IIASA's RAINS model [12, 13]. It is a modular simulation model with sections to calculate: (1) emissions from given levels of activity in the energy sector and energy end uses; (2) subsequent atmospheric transport and chemical transformations of those emissions; (3) deposition; and (4) ecological impacts. The latter are calculated based on a spatial resolution of grid cells of 150 km side length.

The impacts of energy biomass production on land use and potential conflicts with food production were calculated using IIASA's Basic Linked System (BLS) of national agricultural models [22, 23]. BLS consists of sectorially disaggregated macroeconomic models with detailed agricultural production functions that account for all major inputs (land, fertilizer, capital, and labor) required for the production of 11 agricultural commodities.

APPENDIX II: ACRONYMS

AFR – Sub-Saharan Africa
BLS – Basic Linked System model, IIASA
bbl – barrels (oil equivalent, 1 toe = 7 bbl)
CO_2 – carbon dioxide
CO2DB – The IIASA Carbon Dioxide Mitigation Technology Database
CPA – Centrally Planned Asia and China
CPE – commercial primary energy
DCs – developing countries
EEU – Central and Eastern Europe
FSU – Former Soviet Union
GDP – Gross Domestic Product
GDP_{mer} – GDP at market exchange rates
GDP_{ppp} – GDP at purchasing power parities exchange rates
GNP – Gross National Product
GtC – giga [billion (10^9)] tonnes of carbon
Gtoe – giga [billion (10^9)] tonnes oil equivalent
GWP – Gross World Product
IIASA – International Institute for Applied Systems Analysis
IND – industrialized countries (OECD plus REFs)
IPCC – Intergovernmental Panel on Climate Change
kgoe – kilograms oil equivalent
LAM – Latin America and the Caribbean
MEA – Middle East and North Africa
MESSAGE III – Model for Energy Supply Strategy Alternatives and their
– General Environmental Impacts, IIASA
MW – Megawatt
Mtoe – [million (10^6)] tonnes oil equivalent
mer – market exchange rate
NAM – North America
OECD – Organisation for Economic Cooperation and Development
PAO – Pacific OECD
PAS – Other Pacific Asia
PE – primary energy
ppmv – parts per million by volume
ppp – purchasing power parities
RAINS – Regional Acidification INformation and Simulation model, IIASA
REFs – reforming economies (EEU plus FSU)
SAS – South Asia
SG – Scenario Generator model, IIASA
SO_2 – sulphur dioxide
TPE – total primary energy
UN – United Nations
UNDP – United Nations Development Programme
WEC – World Energy Council
WEU – Western Europe
WHO – World Health Organization
11R – 11 world regions macroeconomic energy model, IIASA