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IIASA Working Paper

September 1995

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Working Paper

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WP-95-101
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1. INTRODUCTION

As incomes increase around the world, people will demand more efficient, cleaner, and less obtrusive energy services. That is the central message of the three cases, subdivided into six scenarios, that are presented in the full report of the joint IIASA and WEC study *Global Energy Perspectives to 2050 and Beyond* (1). The scenarios 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 they explore among alternative energy systems, all manage to match the likely, continuing push by consumers for more flexible, more convenient, cleaner forms of energy. This report summarizes the financing requirements of the energy sector needed to achieve these goals, with a particular emphasis on investments in the developing regions.

Capital requirements are assessed according to traditional definitions of energy investments. They include capital for energy production capacities, for conversion and transformation facilities, for transmission and distribution infrastructures, and for complying with environmental standards. Capital requirements for energy end-use devices are not included in this assessment. (Traditionally they are excluded from energy-sector capital requirements and are counted as durable consumer goods and business investments.) The range of the cumulative capital requirements from 1990 to 2020, across the cases, is measured from US(1990)$13 to 20 trillion ($10^{12}$). This is to be compared with the gross world economic product (GWP) of US$21 trillion ($10^{12}$) in 1990. Although both this range and magnitude of capital requirements are enormous, they are less intimidating when viewed in the context of economic growth, investment, savings, GWP and the size of capital markets implied by the scenarios. Capital requirements grow substantially, but more slowly than GWP. This is true in all scenarios, but it does not imply that these capital requirements can actually be raised on domestic and international capital markets for energy investments.

The three cases, subdivided into six scenarios, build on the analysis of the WEC Commission Report *Energy for Tomorrow's World* (2). The development paths of the six scenarios vary through 2020, but after 2020, they start to diverge. Part of that divergence will depend on policy choices and development strategies. For example, two scenarios that assume aggressive international cooperation focused on environmental protection and international equity, lead to less fossil fuel use than the other scenarios. Most of the post-2020 divergence will depend on technological developments and economic restructuring. Which energy sources in 2020 will be

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* An earlier version of this paper was published as a support paper for the Session on "Rural Energy Development and Energy Financing in Developing Countries" at the 16th World Energy Council (WEC) Tokyo Congress held on 8–13 October 1995.

better matched to the more flexible, more convenient, and cleaner forms of energy desired by the consumer? Which will have made the investments in research and development that will give them a technological edge? Which will have shifted their businesses away from providing just tons of coal or kilowatt-hours of electricity toward also providing more flexible, 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 divergence across 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 is wide open now. It will be much narrower by 2020. Today's energy investments, especially in the developing world, will shape future opportunities and financing possibilities.

2. MAIN CHARACTERISTICS OF SCENARIOS

As in *Energy for Tomorrow's World* (2), the joint IIASA and WEC study report *Global Energy Perspectives to 2050 and Beyond* (1) presents three sets of scenarios, Cases A, B, and C. It examines the possibilities beyond 2020 more thoroughly than could be done in *Energy for Tomorrow's World.* The principal focus is on the period between 2020 and 2050, but some preliminary results are also presented up to 2100. In brief, Case A presents a future of impressive technological improvements and 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 ecologically driven" future. It includes both substantial technological progress and unprecedented international cooperation centered explicitly on environmental protection.

The key characteristics of the three cases are summarized in *Table 1* and short descriptions are given in the Appendix. The following paragraphs provide more detail on what they have in common and where they differ.

2.1. COMMONALITIES AMONG SCENARIOS

All three cases provide for significant social and economic development, particularly in the developing countries, and are therefore based on a substantial increase in financing requirements. They lead to improved energy efficiencies and environmental compatibility, and thus for associated growth in both the quantity and quality of energy services.

World population is expected to double to 10 billion (10^9) by 2050 and to increase to nearly 12 billion (10^9) by 2100 (*Figure 1*), while economic development continues throughout the world. According to the scenarios of this study, the result is a three- to five-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 reaches and surpasses levels characteristic of the developed countries today, making current distinctions between the two obsolete. Primary energy consumption grows less than the global demand for energy services due to improvements in energy intensities. *Figure 1* shows a one and a half- to three-fold increase in primary energy requirements across the three cases by 2050, and a two- to five-fold increase by 2100.

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 in 10^{12} US(1990)$			
2050	100	75	75
2100	300	200	220
Energy intensity improvement	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

2.2. DISTINCTIONS AMONG SCENARIOS

Where all six scenarios diverge is in the dynamics of energy system transformation as reflected in the contributions of individual primary energy sources – in other words what percentage is supplied by coal, what percentage by oil, and so forth. That divergence is shown in *Table 2*, which summarizes key numerical characteristics for all six scenarios. It presents a snapshot of how the scenarios would look in 2050.

Figure 2 presents the development over time of the structure of primary energy shares in Case B. Other cases and their underlying scenarios portray different dynamics of future changes in energy sources and in the structure of the energy system. However, the overall characteristic is a continuous shift from fossil to other sources of energy and toward higher quality, more flexible, and cleaner forms of energy delivered to the final consumer.

Assumptions on the most salient forces driving and shaping future energy systems are varied across the scenarios in order to explore both differences and commonalities of alternative future

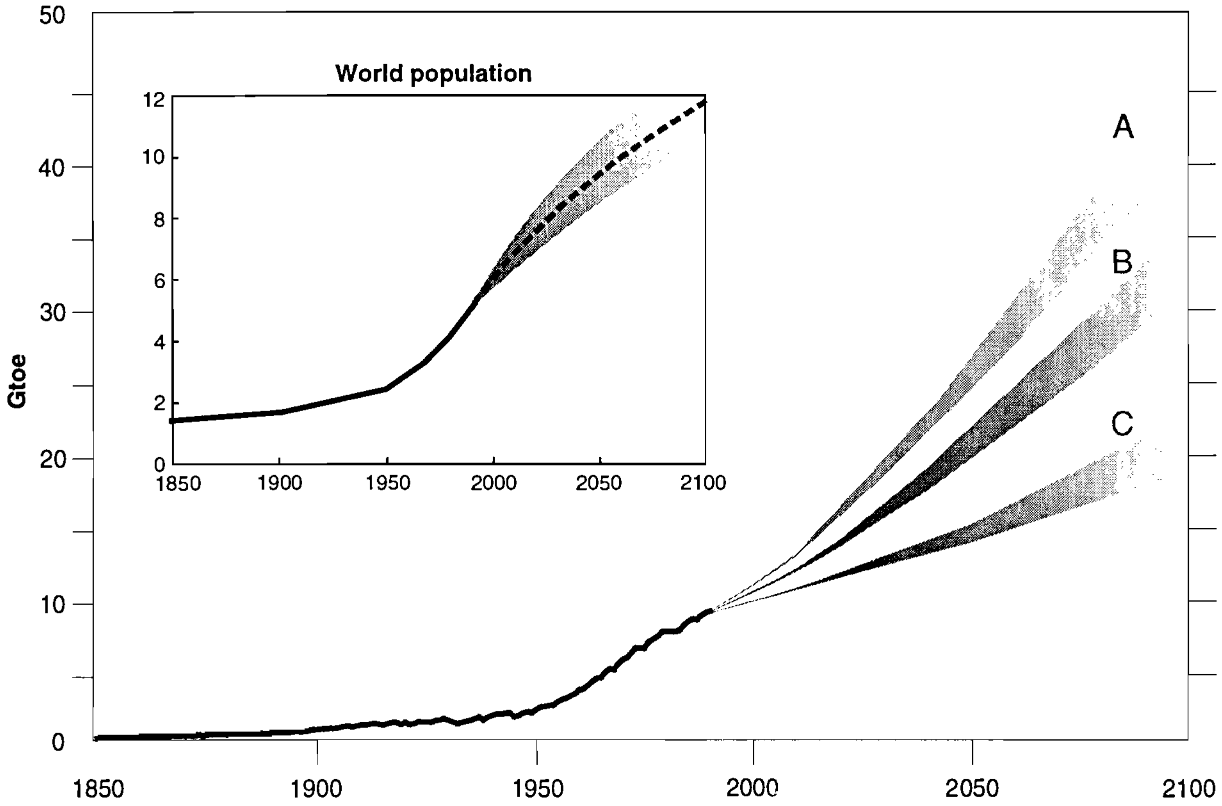

Figure 1: Global Primary Energy Use (Gtoe), 1850 to Present, and in the Three Cases to 2100. The insert shows global population growth, 1850 to present, and its projection (3) to 2100, in billions (10^9) of people.

primary and final energy structures. The scenarios vary with respect to future technologies in terms of penetration rates, performance, and costs; with respect to the availability of energy sources, a question also closely related to technology; and with respect to geopolitical and policy issues, such as trade, technology transfer, environmental regulation, and energy deregulation.

The high-growth Case A consists of three scenarios (A1, A2, A3); Case B, a single scenario; and the ecologically driven Case C, two scenarios (Cl and C2). This reflects the possibility of alternative development strategies with comparable levels of affluence and energy use. The three-pronged unfolding of Case A indicates that high levels of energy demand could be supplied by three fundamentally different strategies that diverge from each other over time. In Case C the differences between the two alternatives considered are less dramatic. For the intermediate Case B a single scenario was developed. In general, this scenario is associated with more modest, perhaps also more realistic, changes; therefore it did not seem useful to consider more extreme alternatives for the development of the energy system. Energy sector investment requirements are given with the greatest degree of detail for Case B, because it is less extreme than the other alternatives and because it illustrates the "middle course" of future financing requirements.

2.3. IMPLICATIONS FOR FINANCING REQUIREMENTS

After having presented the cases and how they unfold into six energy system scenarios we now turn to their implications for investment and financing. All three cases reflect substantial

Table 2: Characteristics of Three Cases, Subdivided into Six Scenarios, for the World in 2050.

	Case					
	A			B	C	
	A1	A2	A3		C1	C2
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[a]	25	27	31	28	29	29
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	1.2	1.7	1.2	1.5	0.9	0.9
Emissions						
Sulfur[b,c], MtS	23	86	15	35	4	3
Nitrogen[c], MtN	21	55	21	22	14	12
Carbon, GtC	12	15	9	10	5	5

[a] District heat, gas, and hydrogen.

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

[c] Preliminary global estimates.

growth for all energy industries to at least 2020, and profound changes beyond, leading to an enormous range and magnitude of capital requirements. The coming decades will bring numerous changes within and between 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 cases indicate prospects will diverge after 2020, with energy industries and consumer needs embarking on mutually exclusive development paths across the six scenarios. All of these developments would have profound implications for future financing requirements. This is reflected in the range of cumulative capital requirements to 2020 – US(1990)$13 to 20 trillion (10^{12}) across the six scenarios.

Despite its huge resource base, coal could be particularly vulnerable due to increased competition from other energy sources and environmental constraints in response to sulfur dioxide, particulate, methane, and carbon dioxide emissions. By contrast the oil industry, and the natural gas industry to an even greater extent, have a long future ahead. The prospects of natural gas

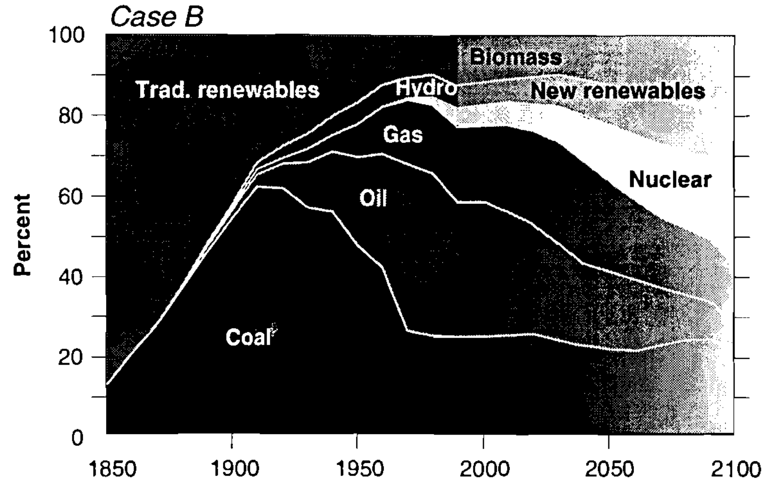

Figure 2: Evolution of Primary Energy Shares, 1850 to 2100, for Case B.

will, however, have to be enhanced by aggressive exploration and resource development. New markets will have to be developed for the traditional fuels, with the recognition that the shift from just selling primary or final energy to marketing energy services will continue and intensify.

In all scenarios renewable energy sources undergo significant expansion. Despite a slower start than depicted in other studies, the outlook given here is clearly bullish in the long run, a view also taken in the WEC's *New Renewable Energy Resources: A Guide to the Future* (4). The development and diffusion of new renewables are seen as requiring several OECD countries to take leading roles with subsequent large technology transfers to developing countries. In the long run the biggest market for renewables will be in the South.

For nuclear power, prospects beyond 2020 are more uncertain. The potential for nuclear energy to make a substantial contribution will depend on whether public concerns about operational safety, waste disposal, and proliferation can be alleviated. If these concerns persist nuclear power could wither away, however it may be successfully challenged to introduce a new generation of facilities that are more acceptable.

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 crucial, 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. Investment decisions to 2020 are, therefore, an important concern – and not simply because of the tremendous sums of money involved. Work also needs to be done to extend the analysis beyond final energy to cover energy services and to examine what new institutional mechanisms are required to facilitate energy financing and the implementation of environmental policies attracting ever-widening support.

We believe this study has identified patterns that are robust across a purposely broad range of scenarios. They can never turn an uncertain future into a sure thing, but they can delimit future energy financing requirements consistent with the range of scenarios.

3. INVESTMENTS AND FINANCING

3.1. ENERGY CAPITAL MARKETS AND INVESTMENTS

Although the capital requirements for all three cases are enormous, they are less intimidating when looked at in the context of economic growth, investment, savings, and the size of capital markets implied by the scenarios. The current average global investment rate is about 22 percent of GWP – 21 percent in the industrialized countries and 24 percent in the developing countries. In the reforming economies, recent gross domestic product (GDP) declines have been matched by reduced savings, keeping the investment rate relatively constant at about 20 percent (5). Although energy investments as a share of economic product and total investments vary greatly among countries and between different stages of economic development, on average, between three to four percent of GDP is invested in the energy sector, and this ratio is expected to remain relatively stable (6). Average ratios of energy to total investments are also quite stable at about 20 percent: approximately 10 percent for power sector investments, and five to 10 percent for upstream operations in the coal, oil, and gas sectors. Deviations from these averages can be as high as a factor of two to three over the next decades. Large energy exporters or rapidly developing countries, for example, experience higher rates.

Capital markets have been growing faster than total GDP for quite some time. Present annual global energy investments amount to at least 10 percent of international credit financing, which is about US$3.6 trillion ($10^{12}$) (7). With capital markets growing relative to GDP, and assuming relatively stable future energy investment ratios, capital market size appears not to be a limiting factor for energy sector finance.

The real challenges in raising funds for energy investments are the perceived risks to investors and adequate rates of return. Returns in the energy sector do not always compare well with many private investment alternatives, not even with other infrastructure investments. Between 1974 and 1992, for example, electricity projects supported by the World Bank realized average rates of return of 11 percent per year, while urban development and transport returns were 23 and 21 percent, respectively (8). Also important is the allocation of funds within the energy sector. Rate of return considerations discriminate against smaller-scale, clean, and innovative energy supplies, and against investments in energy efficiency improvements. Market size and product mobility often favor investments in oil exploration over, for example, natural gas or energy conservation.

Until now, in many countries much of the energy sector has been publicly owned, and in most developing countries substantial international funding has supplemented limited domestic capabilities. The share of private sector capital has usually been less than 20 percent. More recently, growing public and private debt in industrialized and developing countries alike has made energy sector financing, with its long amortization periods, more difficult. Privatization has become the accepted political remedy. A second development increasing the likely dependence of energy investments on private capital, is stagnation in international development finance, despite an increase in international credit financing from five percent of gross world product, or about US$175 billion ($10^9$) in 1973 to 17 percent, or about US$3.6 trillion ($10^{12}$) in 1993 (7). Although energy financing therefore must increasingly come from the private sector, government policies can make a difference by restructuring subsidies that reduce noncommercial investment risks consistent with long-term development targets, by encouraging energy prices that reflect real costs, and by maintaining a stable political climate that reduces investment risks and broadens access to international capital markets. Nonetheless, the bottom line for energy investments remains unchanged: returns must at least match opportunity costs.

Table 3 quantifies the cumulative energy sector capital requirements for Cases A, B, and C, according to traditional definitions of energy investments. They include capital for energy production capacities, for conversion and transformation facilities, for transmission and distribution infrastructures, and for complying with environmental standards. They do not include investments in end-use technologies such as furnaces, appliances, and vehicles, because they 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 three cases in this study is a strong argument in favor of new approaches to evaluating energy sector investments. Integrated resource planning, for example, has begun to extend the traditional energy sector perspective to include investments in end-use technologies. Approaches that assess both supply options and end-use options, and both expansion and conservation will be increasingly essential in all the futures represented by the three cases.

A simple "back of the envelope" calculation can be used to illustrate the need to widen the definition of energy investments to the whole energy system including end use. Case C relies heavily on measures to improve end-use efficiencies. For the period 2020 to 2050, *Table 3* shows cumulative investments in Case C to be only slightly more than half of the investments in Case A. Compared with Case B, Case C has the same GWP, but the traditional energy investments are US$400 billion ($10^9$) less, or only 64 percent of the investments in Case B. This looks almost like a "free lunch." This picture may change drastically if investments in end-use technologies are included. Case C uses 4 Gtoe less final energy or 6 Gtoe less primary energy than does Case B (see *Table* 2). Assume that this reduction is achieved with additional investments for more efficient end-use equipment and devices at levelized investment costs comparable to average energy sector investment needs. For example, an average investment of US$50/toe (see *Tables* 2 and *3*) would lead to total additional end-use capital requirements of US$300 billion ($10^9$) by 2020 for a reduction in primary energy needs of 6 Gtoe. This simple calculation suggests that the total investments in the energy system for Case C could be of the same magnitude as for Case B. However, should end-use investments turn out to be higher or lower than assumed in this overly simplistic calculation, the relative attributions could change radically.

3.2. INVESTMENT REQUIREMENTS AND TECHNOLOGICAL CHANGE

Future specific investment costs, especially for new energy technologies, can depend on the cumulative learning effects. The three cases incorporate future technological improvements in performance and capital cost reductions with increasing diffusion, especially of new technologies such as photovoltaics, hydrogen production, or fuel cells. Capital costs of many conventional technologies also decline, albeit at a much slower rate due to the inherently incremental improvement of mature technologies.

The full report of the joint IIASA and WEC study devotes considerable space to the dynamics of technological progress and to technological innovation and diffusion, drawing on the inventory of 1400 technologies (9,10). We pooled all available estimates of investment requirements from the inventory so that the respective medians and ranges could be extracted from the data. For example, investment costs for solar systems and nuclear reactors were derived from 45 and 34

Table 3: Cumulative Investments in Energy Sector by Region, 1990–2020 and 2020–2050.

	Case					
Energy	A[a]		B		C[b]	
investments	1990–2020	2020–2050	1990–2020	2020–2050	1990–2020	2020–2050
Cumulative in 10^{12} 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.

- OECD: Countries members of the Organisation of Economic Co-operation and Development;
- REFs: Countries with reforming economies;
- DCs: Developing countries.

independent estimates, respectively, as shown in *Figure 3*. Near-term investment requirements assumed for the three cases were derived from the medians of the empirical cost distributions. Lower ranges defined the scope for future cost reductions along the learning curves that are realized at different rates in the three cases.

The "learning" or "experience" curve characterizes the pattern of diminishing costs with increasing cumulative production. Its specific shape depends on the individual technology in question, but it is a persistent characteristic of all successful, standardized technologies. Usually there are steep cost improvements during the research and development phase. For example, *Figure 4* shows an 18 percent reduction in investment costs per doubling of cumulative production of combustion turbines. These are followed by more modest improvements after commercialization – for combustion turbines, seven percent per production doubling. Improvements continue for some time at a slower pace and then cease as the technology approaches the end of its life cycle (13).

Cases A, B, and C incorporate technological change through learning curve effects for various individual and generic technologies. These reflect different priorities and varying impacts of related features, such as international trade in some technologies and the scope for local development and manufacture of others.

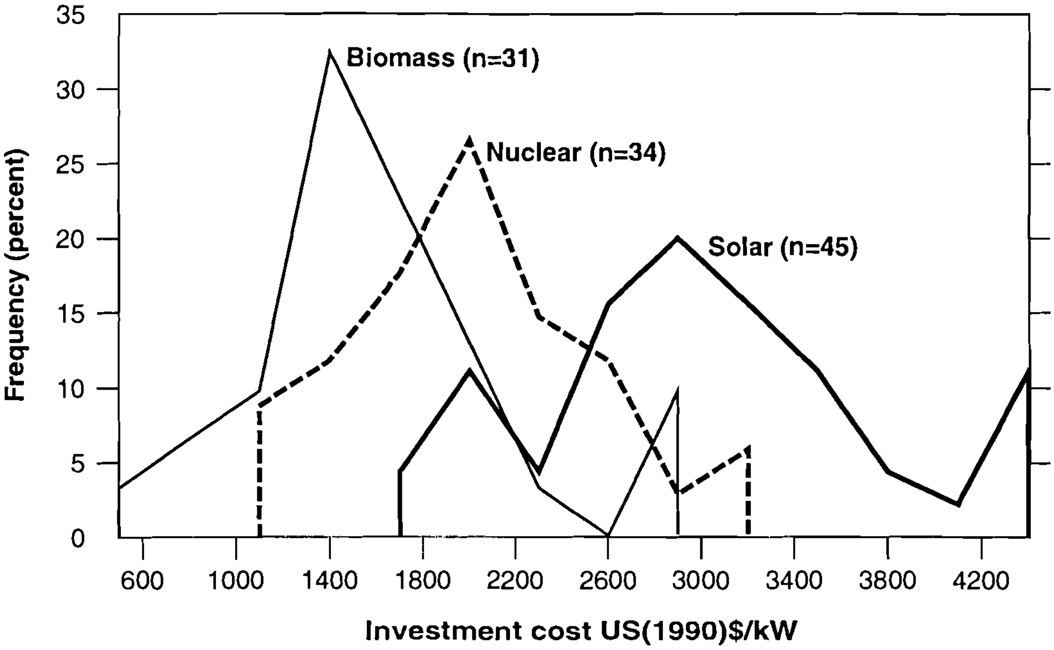

Figure 3: Range of Investment Cost Distributions as a Histogram Used to Assess Current and Future Financing Requirements (n=number denotes the sample size).

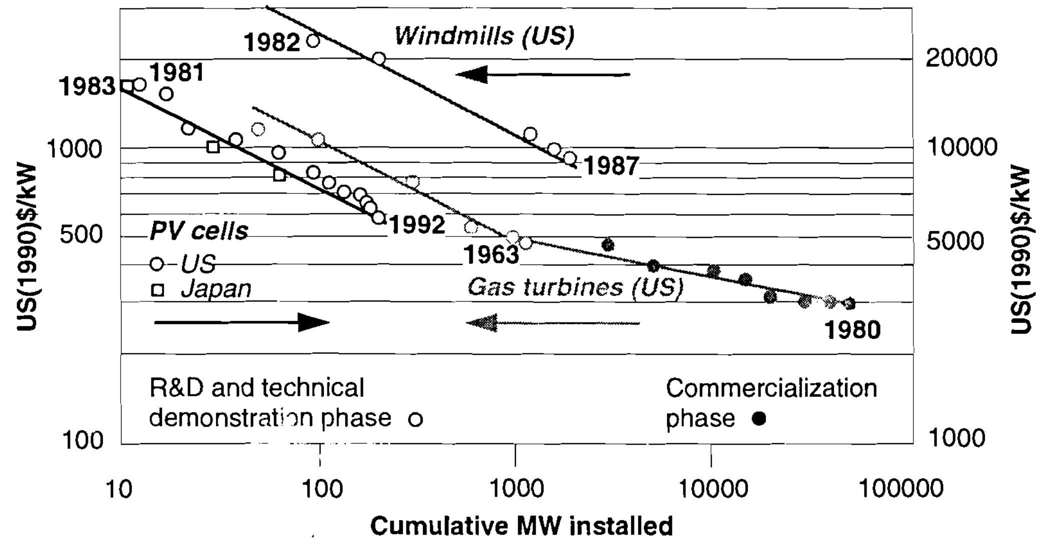

Figure 4: Technology Learning Curves. Improvement in the costs per unit of capacity versus cumulative installed capacity. Sources: Adapted from MacGregor *et al.*, (11); and Christiansson, (12).

In Case A there is substantial advancement of all new, and currently marginal, energy production and conversion technologies. These advances are demonstrated across the board: for hydrocarbon exploration and extraction; for nuclear electricity generation and hydrogen; and for renewable sources of electricity generation and biofuel production and conversion. In Case B the advances are less substantial than in Case A, reflecting less concentrated research, development and diffusion efforts. In this respect Case B lags behind Case A by 30 percent. The bulk of the effort in Case B is put into incremental improvement of existing technologies consistent with the case's less concerted research and development efforts. 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.

Technological change leads to capital cost reductions in all cases with increasing scale of new technology deployment. This means that the future capital costs in the joint IIASA and WEC study might be smaller due to technological change compared with other studies that assume more static technological development.

There are other reasons for a possible overestimate of actual capital requirements. All cases explicitly adopt a cost-optimal structure of the energy system. Reality might be different, especially if the chronic lack of capital continues to trouble the developing world. Replacement of old vintages might be postponed, leading to lower capital requirements. However, if departures from the outlined investment trajectories are too great, they may lead to energy supply shortages and thus to a loss of economic output, which would then be lower than assumed in the three cases.

On the other hand, the possibility of underestimation cannot be ruled out either. For example, it is difficult to accurately account for the long-term ratio of peak-to-base load capacity, and the peak capacity may be higher than anticipated in the three cases. Also, if natural gas supplies cannot be brought to the market place at the rate indicated, the relatively low capital intensive natural gas-fired electricity generation needs to be replaced by more capital intensive coal or hydropower plants, cumulative investments may turn out to be higher than calculated in the joint IIASA and WEC study. On the whole, capital requirements implied by the three cases can be considered to represent a realistic and a detailed account of the financing needs of these three alternative futures.

3.3. ENERGY INVESTMENTS IN THE THREE CASES

Looking first at the cumulative capital requirements from 1990 to 2020, *Table 3* shows the range across the cases to be from US(1990)\$13 to 20 trillion (10^{12}). The developing region's share rises sharply from today's 25 to 30 percent to between 42 and 48 percent, and it becomes the largest energy capital investment market in all cases. Looking at energy investments as a share of regional GDP, the reforming countries rank the highest, diverting seven to nine percent of the regional GDP to the energy sector. They will be burdened by slow initial economic growth; at the same time they will need to replace obsolete energy infrastructures, and it is likely to be extremely difficult to attract the needed capital to the energy sector. Developing countries invest three to four percent of GDP in the energy sector, and OECD region investments are the lowest at 0.8 to 1.1 percent of GDP. By and large, it takes a greater effort to build up an energy infrastructure than to expand and maintain an existing one. Finally, the bottom section

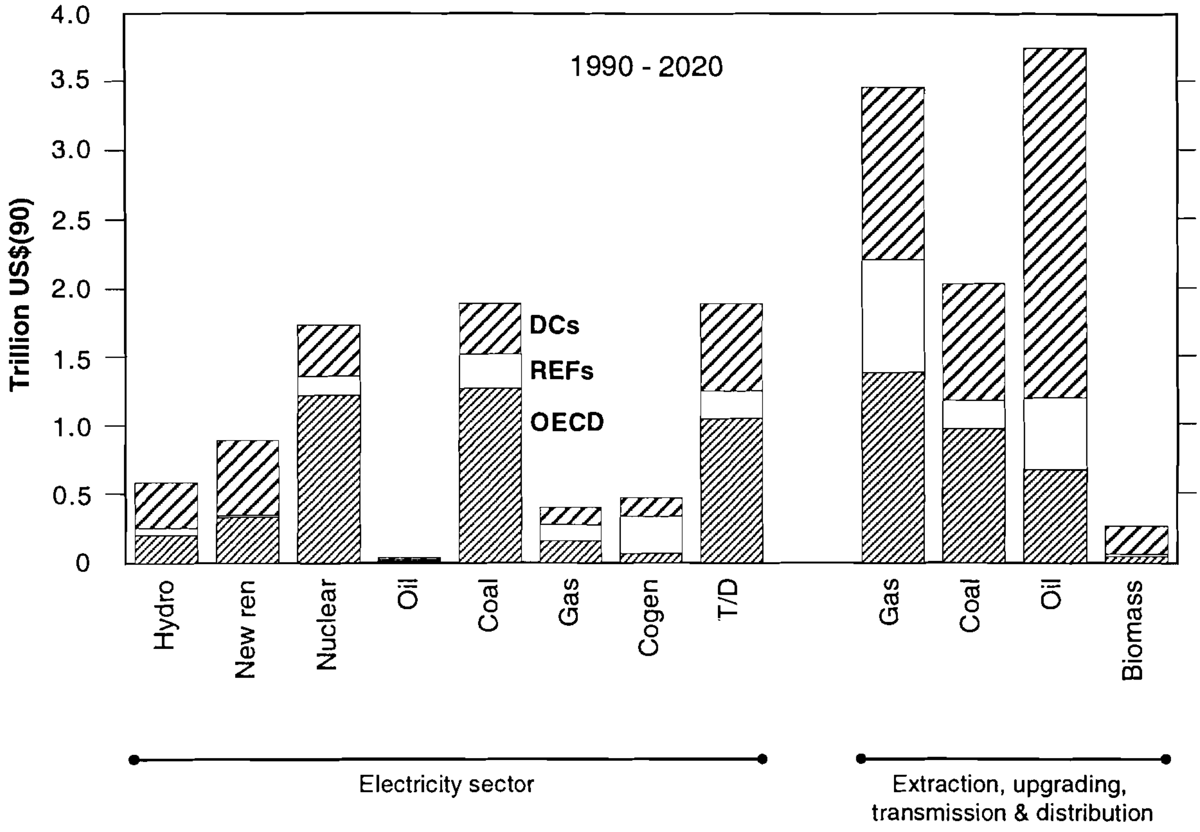

Figure 5: Breakdown of Global Cumulative Energy Sector Investments for Case B from 1990 to 2020, in trillion (10^{12}) US(1990)$.

of *Table 3* shows an upward trend for specific investments (US$ per unit primary energy) in all cases, even though future energy investments do not increase relative to GDP.

To illustrate what goes into the cumulative capital requirements of *Table 3*, *Figure 5* breaks down the different components for Case B. The figure shows that investment in electricity generation is dominated by the OECD, especially for the expansion of nuclear and coal-fired capacity. New renewable and hydropower investments are concentrated in developing regions. Given the current economic unattractiveness of most new renewables, this reflects substantial learning curve effects. Over US$250 billion ($10^9$) are invested in the development of a bio-fuel production infrastructure. The accepted view that oil and gas generally are profitable investment opportunities is reflected both by the volume and regional breakdown in the figure.

From 2020 to 2050, capital requirements in *Table 3* grow substantially in absolute terms, but still more slowly than GDP. This is true in all scenarios. It reflects, first, the shift from supply-side investments (included in *Table 3*) to end-use technology and infrastructure investments (not included in *Table 3*). Had we been able to include the latter, we estimate it might have increased the numbers by 50 to 100 percent. Second, the declining share of GDP going to energy investments reflects continued progress along technological learning curves throughout the energy system. Had these been excluded, the capital requirements of the electricity sector in the OECD region would have been eight to 15 percent higher for 1990 to 2020. In developing regions, the impact would have been greater, an increase of 25 to 40 percent, due to heavy investments in new renewables and hydropower. Finally, and most importantly, capital requirements grow slower than GDP because of the continuation of energy intensity improvements, characteristic for all three cases.

3.4. OTHER ESTIMATES OF FINANCING REQUIREMENTS

The figures in *Table 3* are consistent with the estimates of *Energy for Tomorrow's World* (2). There, the estimated global capital requirement for 1990 to 2020 was US\$30 trillion (10^{12}). This included efficiency improvement-related investments of approximately US\$7 trillion (10^{12}) which are excluded here, but excluded learning curve effects in lowering future investments which are included here. Once both corrections are made, the figures are consistent. *Energy for Tomorrow's World* was also used as the basis for a simplified analysis by Hyman (8). Assuming an average capital cost of US\$750 per kW of generating capacity, he calculated total 1990 to 2020 investment requirements to be US\$4.3 trillion (10^{12}) for the electricity sector. For comparison, our detailed calculations estimate requirements to be 75 to 125 percent higher.

Annual capital requirements for energy investments rise from a little less than US(1990)\$400 billion (10^9) in 1990, to US(1990)\$500 to 750 billion (10^9) by 2020, and US(1990)\$0.7 to 1.2 trillion (10^{12}) by 2050. A large share of this investment would probably need to be externally financed. Hyman (8) estimates that a third of the global capital spending based on *Energy for Tomorrow's World* (2) electricity needs would be externally financed. This implies that a large share of total energy investments would also need to come from international capital markets or development assistance. That compares with total funds transferred to developing countries in 1990 of about US\$140 billion (10^9), to a total debt service for these countries of about US\$150 billion (10^9), and to total official development assistance from the OECD countries of about US\$50 billion (10^9) (14).

As its title suggests, the WEC report on *Financing Energy Development: The Challenges and Requirements of Developing Countries* (15) investigated the challenges facing energy financing in the developing countries. The approach pursued by that study complements the approach of this joint IIASA and WEC study in many respects. While the joint IIASA and WEC study made extensive use of formalized models to assure consistency between economic development, energy service demand, capacity buildup rates, resource development, and extraction grounded on detailed technology cost data, the WEC study on developing countries drew on the expertise of many individuals and institutions including international development banks. The study focused more on the institutional and policy aspects, financing mechanisms, regulation, foreign investment, the role of international development agencies, etc., and less on detailed calculations of energy investment requirements. The joint IIASA and WEC study accounted for the investment needs on a technology-by-technology basis separately for production, conversion, transmission and distribution. The specific investment costs are dynamic and account for learning curve and economies of scale effects. It should also be noted that the underlying energy development scenarios have not been harmonized between the two groups. Finally, the geographical and temporal scopes differ: the joint IIASA and WEC study includes the entire world up to the year 2050 in greater detail and to 2100 in outline, while the WEC study on developing countries considers the time period 1990 to 2020.

One should note another fundamental difference when comparing the sets of investment requirements produced by the two groups. The WEC study on developing countries excludes investments for energy exports in their estimates. The investment volumes reported are based

Table 4: Cumulative Energy Investment Requirements in Developing Countries. Reproduced from the WEC report (15), 1990–2020, in trillion (10^{12}) US(1990)$.

Sector	Latin America	MENA[a]	Sub-Saharan Africa	DCs Pacific	South Asia	All DCs
Electric power	1.10–1.80	0.30–0.50	0.20–0.40	0.53–1.12	0.30–0.60	2.43–4.42
Oil[b]	0.07–0.24	0.06–0.16	0.04–0.13	0.03–0.13	0.06–0.12	0.26–0.78
Natural gas	0.03–0.07	0.06–0.08	.002–0.04	0.01–0.03	0.01–0.03	0.11-0.25
Coal	0.01-0.03	0[c]	.003-0.03	0.03–0.07	0.01–0.05	0.05–0.18
Biomass and renewables	0.06–0.40	0.01-0.06	0.03–0.17	0.08–0.41	0.05–0.19	0.23–1.23
Total	1.27–2.54	0.43–0.80	0.28–0.77	0.68–1.76	0.43–0.99	3.08–6.86

[a] MENA: Middle East and North Africa.

[b] Includes refining.

[c] No additional capacity required.

Table 5: Cumulative Energy Investment Requirements in Developing Countries Based on Cases A[a], B, and C[b], 1990–2020, in trillion (10^{12}) US(1990)$.

Sector	Latin America	MENA[c]	Sub-Saharan Africa	DCs Pacific[d]	South Asia	Centrally Planned Asia	All DCs
Electric power	0.31–0.38	0.16–0.22	0.16–0.21	0.45–0.63	0.33–0.46	0.74–1.15	2.15–3.03
Oil[e]	0.49–0.71	0.85–1.42	0.24–0.43	0.11–0.24	0.02–0.04	0.26–0.38	1.97–3.22
Natural gas	0.27–0.32	0.50–0.60	0.03–0.04	0.13–0.16	0.16–0.25	0.12–0.17	1.25–1.49
Coal	0.03–0.04	0[f]	0.11–0.33	0.04–0.04	0.10–0.12	0.44–0.79	0.72–1.32
Biomass and renewables	0.03–0.06	.007–0.01	0.03–0.08	0.03–0.03	0.01–0.03	0.07–0.18	0.25–0.30
Total	1.20–1.46	1.61–2.13	0.63–1.03	0.77–1.10	0.72–0.81	1.65–2.67	6.59–9.20

[a] A1 scenario.

[b] C1 scenario.

[c] MENA: Middle East and North Africa.

[d] Range for coal and biomass is too small at the level of significance.

[e] Includes refining.

[f] Investments are very low.

on meeting developing countries' energy demand only. Also unclear is whether the volumes include the investments for the replacement of retired plants and equipment. In addition, no capacity cushions are factored into the estimates for upstream oil and gas investments.

The longer time horizon of the joint IIASA and WEC study introduces a distinctly different investment profile than is found in the more static calculations of the WEC study on developing countries. Construction times for new power plants can be as long as a decade or more. Therefore, the construction starts of capacity additions scheduled to connect to the grid in the early 2020s will take place during the 2010s. Consequently, the financing needs arise during that decade and are included in the 1990 to 2020 cumulative investment requirements.

Table 4 summarizes the energy investment requirements in the developing countries for the period 1990 to 2020, reproduced from the WEC report (15); *Table 5* summarizes investment requirements from the joint IIASA and WEC study. The agreement between the two studies is surprisingly high given the fundamentally different study approaches and underlying methodologies. The first notable difference (see *Tables 4* and *5* and *Figure 6*) concerns the total investment volume. The lower range of the joint IIASA and WEC study of US$6.6 trillion ($10^{12}$) barely overlaps with the upper range of the other estimate of US$6.9 trillion ($10^{12}$). The lower range estimates differ by a factor of two versus a factor of one and a half for the upper ranges. The sectoral breakdown reveals that the upstream investments in oil, natural gas and coal exceed those of the WEC study on developing countries by an order of magnitude. Electric power development investments, however, agree reasonably well between the two studies. Here, the estimates of the WEC study on developing countries are somewhat higher, which can be attributed to the static specific investment costs used in the calculations. In addition, the share of hydropower in electricity generation is generally 50 percent higher than in the joint IIASA and WEC study. The rapid hydropower capacity expansion implies the utilization of fairly capital intensive hydro resources. In contrast, the joint IIASA and WEC scenarios indicate an intensification of thermal power generation based on natural gas. Natural gas turbines tend to be considerably less capital intensive than hydropower. In this context, it is important to note that in the joint IIASA and WEC study specific investment costs are different for domestically manufactured generating technologies and for technology imports. Conventional plant and equipment is assumed to be largely of domestic origin and thus carries a lower price tag than the comparable equipment in the OECD; the costs of more complex plants are essentially uniform across the regions.

The order of magnitude differences in the upstream sector investment volumes arise from the large net fossil exports from the DC's primarily to the OECD, as well as the construction of an elaborated natural gas infrastructure. By the year 2020, net exports range between 660 Mtoe and 1050 Mtoe (the latter is approximately the 1990 volume), the bulk of which is Middle East oil exports. In addition, all developing regions accelerate oil and gas exploration over the coming 30 years to meet growing domestic demand and to curb depletion of national income driven by oil imports. Several regions begin the development of capital-intensive nonconventional oil reserves after 2010. A considerable amount of capital is absorbed by the expansion of energy transmission and distribution infrastructures.

3.5. ENERGY TAXES AND REGULATION

The Case C scenarios deserve a special mention because of the regulatory measures (e.g., taxes) that they incorporate to accelerate energy intensity improvements and to limit carbon emissions; this does not mean that new energy taxes would not be needed in other cases, but in Case C they are imposed explicitly. This gradually increases the real cost of energy to consumers by approximately a factor of four between 1990 and 2050. Tax revenues from the OECD region are transferred to the developing countries, and revenues from developing countries are recycled internally. The transfer of resources to the South results in a reduction in economic growth in the North. However, the potential impact of energy taxes is much larger in the South. First, the capital infusion from the North is not enough to offset the higher real cost of energy. Second, the impact depends on how productively tax revenues can be used. Taken together, these effects cause the 1990 to 2020 economic growth rates in Case C to fall behind those in Case A. However, in the longer run (post 2050), the transfer of funds to the South leads to GDP growth rates in Case C that exceed those in Case A. In the end, Case C's GDP in the South approaches that of Case A and in any case is substantially higher than in the non-cooperative Case B. This hypothetical case illustrates that capital transfers from energy tax

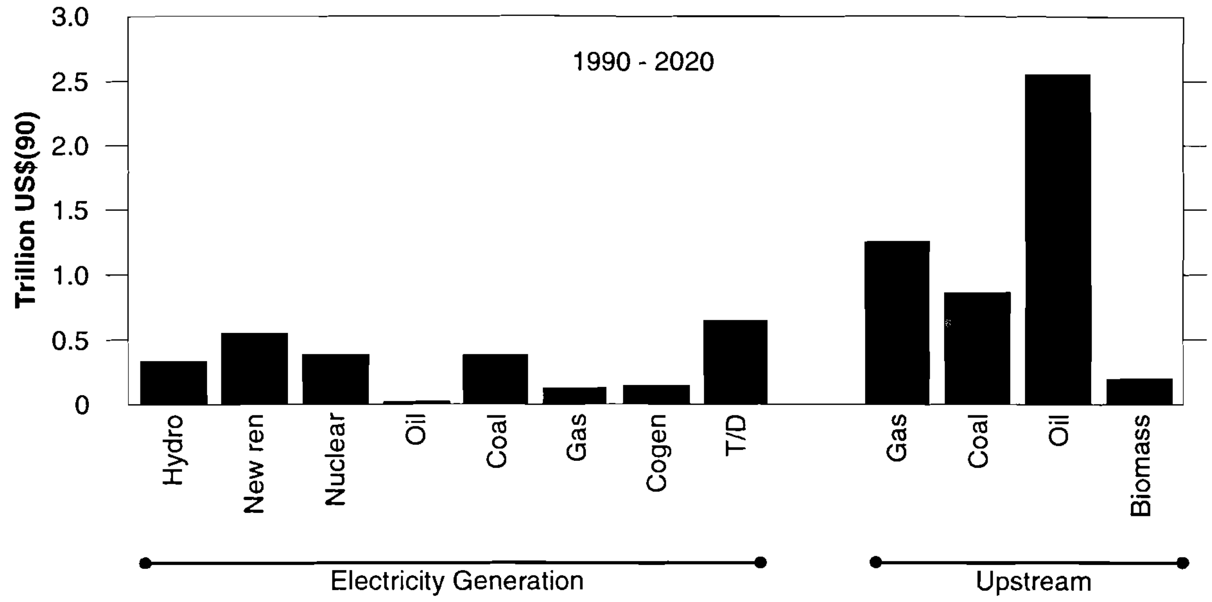

Figure 6: Cumulative Energy Sector Capital Requirements in Developing Countries for Case B, 1990–2020, in trillion (10^{12}) US(1990)$.

revenues could be in principle used for easing capital shortages in the developing countries, but that it requires an unprecedented degree of international cooperation. The relationship between energy regulatory and tax policies and investment is an important issue for the future assessment of energy financing requirements.

4. CONCLUSIONS

For all scenarios the capital requirements of the energy sector are extremely large, but not infeasible. The good news is that investment requirements are likely to expand at a slower pace than overall economic growth. But there are two pieces of bad news. First, the energy sector will have to raise an increasing fraction of its capital from the private sector, where it will face stiffer competition and return on investment criteria than it has in the past. Second, most of the investments that need to be made are in the developing countries, where current trends in the availability of both international development capital and private investment capital are not auspicious. The longer-term prospects of overall economic growth outpacing energy capital requirements are no reason for complacency. The most difficult investment challenge is usually the next power plant, pipeline or refinery. Unlike energy resource requirements where uncertainty and potential difficulties are of a longer-term nature, capital requirements and finance need to be addressed and dealt with now. Today's investment will shape the immediate future, as well as the long-term options.

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APPENDIX: SHORT DESCRIPTION OF THE THREE CASES

Case A (High Growth) is characterized by enormous productivity increases and wealth. It is technology and resources intensive and presumes favorable geopolitics and free markets. 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, global average per capita income surpasses even the highest levels observed today and current distinctions between "developed" and "developing" regions become obsolete. Case A includes three scenarios addressing alternative key developments in energy supply. In the A1 scenario, there is ample future availability of oil and gas resources. At the other end of the spectrum, the A2 scenario assumes oil and gas resources are more limited, resulting in a massive return to coal. Finally, in the A3 scenario 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. This unfolding into three different development trajectories results in three scenarios with almost identical energy end-use patterns but different energy system structures.

Case B (Middle Course), with a single scenario, is based on a more cautious approach regarding economic growth prospects, rates of technological change, and energy availability. In short, the scenario is perhaps best characterized by "modest dynamics" and derives its appeal primarily because it is "pragmatic." Overall, the Case B scenario is "reachable" without relying on drastic changes in current institutions, technologies, or current perception of availability of fossil fuel resources. The more modest energy use compared with Case A implies that scenario B can rely on fossil fuel resources to an extent that is commensurate with current estimates of ultimately recoverable oil and gas reserves. Energy supply and end-use patterns are also closer to the current situation for a longer period in Case B than in Cases A and C. Beyond 2020, however, the depletion of fossil resources without counterbalancing technological progress will force more dramatic changes in energy supply structures. Nonetheless, a transition away from fossil fuel use is feasible and manageable. In the very long-term, the changes become much more dramatic, and an orderly transition away from fossil fuel use is not only feasible but appears to be manageable in terms of energy sector and institutional adjustments extending toward the end of the 21st century.

Case C (Ecologically Driven) presents challenging global perspectives. It is optimistic about technology and geopolitics, but it also assumes unprecedented and aggressive international cooperation focused explicitly on environmental protection. It builds on substantial resource transfers from North to South, spurring growth in the South that will lead to a significant reduction in present economic disparities. In addition to stringent control of local and regional pollutants, a global regime to control the emissions of greenhouse gases is established. The goal is to reduce CO_2 emission levels to 2 GtC by 2100, [corresponding to one-third of 1990 levels required to stabilize atmospheric concentrations (16)]. Ambitious policy measures accelerate energy efficiency improvements and develop and promote environmentally benign, decentralized energy technologies. One policy option considered for achieving this goal is a carbon tax that gradually increases to US$400 per tC in 2100. Case C describes a transition away from the current dominance of fossil fuels toward a dominance of renewable energy flows. The quality of the energy carriers delivered to end users is high in order to meet the environmental constraints so that renewable energy sources are transformed into electricity, liquid, and gaseous energy carriers. Nuclear energy is at a crossroads and this constitutes the main difference between the two Case C scenarios.