World Population, Economic Growth, and Energy Demand, 1990-2100: A Review of Projections

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World Population, Economic Growth, and Energy Demand, 1990–2100: A Review of Projections

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THE PURPOSE OF THIS ARTICLE is to assess some current projections of world population, economic product, energy consumption, carbon dioxide emission, and atmospheric carbon dioxide concentration. The focus and main reference point of the discussion will be clarification of projections made by the World Energy Council (WEC).[1] These projections are described in detail in the report *Energy for Tomorrow's World* (WEC 1993).

The Introduction of the WEC report states: "The year 2020 was selected as the main time-horizon for this Commission, but, recognising that some major energy issues are likely to come to a head after this date, possibilities out to the year 2100 were also considered." Four energy projections for 2020 are given, three of which are extended to 2100. The report mentions that "many other Cases could have been considered, with rapidly diminishing returns—especially those with long time-horizons." The present article develops four supplementary projections for 2020 and one additional scenario for 2100.

The WEC projections are given in terms of primary energy, or the thermal energy released by the combustion of hydrocarbons (coal, oil, and natural gas) and carbohydrates (biomass). The unit of primary energy is the metric ton (tonne) of oil equivalent (toe), equal to 42 gigajoules (GJ). (A gigajoule equals a billion joules; a megajoule equals a million joules.) The primary equivalent of a given amount of nonfossil (hydro, nuclear, etc.) electricity is the amount of thermal energy that would be needed to generate it in a fossil-fueled power plant operating at an efficiency of 38.46 percent (assumed to be the world average). One kilowatt hour (kWh, or 3.6 megajoules) of nonfossil electricity is thus counted as equivalent to 2.60 kWh (9.36 MJ) of primary energy. One terawatt-hour (TWh) of nonfossil electricity is equal to 0.223 million toe (Mtoe) of primary energy.

Smil has criticized this procedure on two counts, although he accepts that there is no satisfactory alternative (Smil 1994). First, the assumed efficiency should be adjusted annually with the changing efficiency of thermal generating stations. But the efficiency rise in the period 1990–2020 is unlikely to be more than a few percentage points, as almost all thermal plants built after 1980—and many built earlier—will still be in service in 2020, and steam turbine plants are likely to remain the dominant type. Second, the procedure "disadvantages" countries with a high per capita hydroelectricity production (Norway, Sweden, Canada), because it inflates their energy consumption in terms of oil equivalent, making them appear less energy-efficient. But this applies only to comparisons between countries; at higher levels of aggregation (Western Europe, North America) the effect is small.

The following groupings of the world's countries are used:

The UN classification

—More developed countries (MDCs): United States, Canada, Europe, Commonwealth of Independent States (CIS), Japan, Australia, and New Zealand;
—Less developed countries (LDCs): All other countries.

The WEC primary classification

—Organization for Economic Cooperation and Development (OECD) (excluding Mexico, admitted in April 1994);
—Central and Eastern Europe (CEE) and CIS;
—Developing countries (DCs).

The difference between the WEC developing country category and the UN less developed country category is that the former excludes Turkey, which is a member of OECD. Both the UN and the WEC classifications could be improved: Hong Kong, Israel, Singapore, South Korea, and Taiwan are industrialized countries; Turkey and the Central Asian republics of the CIS (Kazakhstan, Kirgizistan, Tadjikistan, Turkmenistan, and Uzbekistan) are developing countries. However, these are minor defects that do not affect the utility of the classifications for preparing global projections.

The WEC secondary classification

—North America (Canada and the United States);
—Latin America and the Caribbean;
—Western Europe (including Turkey);
—Central and Eastern Europe;
—CIS (including all republics of the former Soviet Union);

—Middle East and North Africa;
—Sub-Saharan Africa;
—Pacific (including Japan, Australia, and New Zealand);
—South Asia.

This classification "cuts across" the primary classification, as the Pacific region includes three OECD members, the other countries of the region being DCs.

The WEC energy projections have been computed for each of the nine regions, and the results aggregated for the three major groupings and the world.

Population

Population plays no direct part in calculating the energy demand projections of the WEC, because future energy demand is considered to be a function of an assumed rate of economic growth and an assumed rate of decline of energy intensity. (The energy intensity of a country is its primary energy consumption divided by its gross domestic product.) Nevertheless, it is necessary to adopt a population projection in order to make projections for GDP per capita, the principal indicator of the average level of economic development in a country or region, and to make comparisons between countries in terms of energy consumption per capita.

The WEC uses the 1990 UN "medium" projection, according to which the world population will increase from 5,292 million in 1990 to 8,092 million in 2020. The 1992 revision of the UN "medium" projection is 8,050 million in 2020 (United Nations 1993). The 1992 UN "high," "medium," and "low" projections for the MDCs, the LDCs, and the world in 2020 are given in Table 1.

The WEC report tabulates "high," "medium," and "low" projections for world population in the period 1990–2100. The projections are shown in Figure 1, together with the corresponding variants of the UN long-range projections (United Nations 1992).

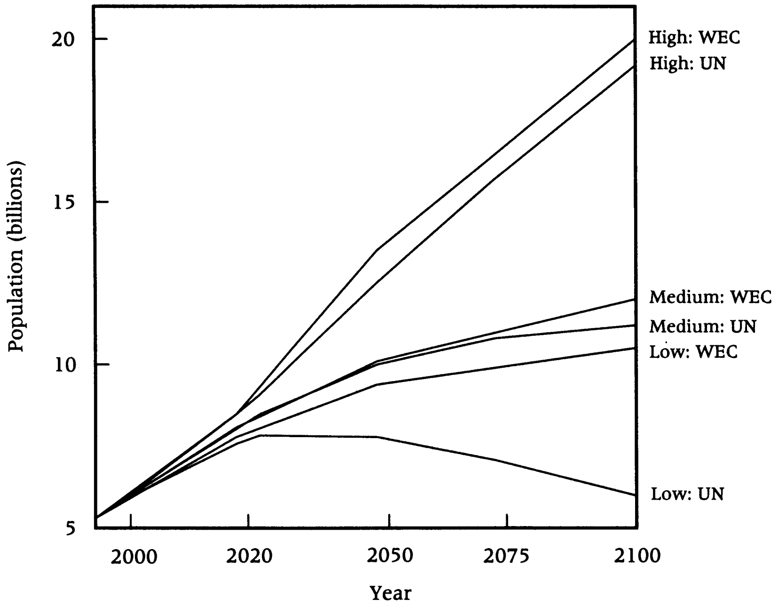
The UN "low" projection is much lower than the "low" projection adopted by the WEC. It is based on the assumption that the global average

TABLE 1 Estimated population in 1990 and projected population in 2020 (millions)

		2020		
Region	**1990**	**High**	**Medium**	**Low**
MDC	1,211	1,465	1,387	1,295
LDC	4,084	7,033	6,663	6,286
World	5,295	8,498	8,050	7,581

SOURCE: UN 1993.

FIGURE 1 World population projections 1990–2100



SOURCES: WEC 1993; UN 1992, 1993

fertility rate will decline to 1.70 births per woman in 2100–05. This implies that at least one-third of all women will either be childless or have only one child. Fertility rates below 1.7 already prevail in a number of OECD countries, including Germany, Italy, and Spain, and fertility in the former East Germany reached an unprecedented low of approximately 0.75 in the first half of 1993 (Eberstadt 1994). Nevertheless, it may be considered highly unlikely that the world average fertility rate—3.4 in 1985–90—will be halved by the end of the twenty-first century.

The WEC "high" variant—a world population of 20 billion in 2100—cannot be ruled out, but would be practically certain to involve a decline in world average food and energy consumptions per capita, and would probably involve population stabilization via rising mortality in many countries. However, this would be disputed by those who believe that economic growth and technological advance can overcome the natural resource constraints that such a global population size would impose.

Cogent arguments have been advanced on both sides of the world population–natural resources debate. Those who hold that resources must sooner or later constrain population growth point out that:

> [M]odern Western civilisation contains exceptionally strong and varied inhibitions against facing the idea that a serious population–resources problem can and does exist. An optimistic materialism grew naturally out of the vast

> 19th-century successes in both technological and geographic expansion. This materialism permeated equally strongly the Marxist-Communist, the liberal-capitalist and the social-democratic political creeds. (Political and Economic Planning 1955: 307)

Most of those who take this view would probably agree with Georgescu-Roegen that exponential economic growth is a "historical interlude caused by a unique mineralogical bonanza" (Georgescu-Roegen 1979: 97).

A recent restatement of the opposite view is given by the civil engineer John Breen:

> Almost 200 years ago, Malthus, in his "Essay on the Principle of Population", predicted a dire future because he believed growth in food supplies would be rapidly out-paced by a geometric growth in population. With two centuries' hindsight, we know that Malthus erred seriously because he did not foresee the technological progress and ingenuity of a scientific agriculture. In his food production estimate he was a *Prisoner of the Familiar*. Today, there is similar concern over energy resources. (Breen 1994: 71)

Breen's statement is correct as far as it goes. As agronomist L. T. Evans has stated, "it is the interactions and unforeseen synergisms not only between [plant] breeding and agronomy, but between all the disciplines, that have kept Malthus at bay" (Evans 1993: 389). Above all, Malthus failed to foresee the synergism between chemical engineering and plant breeding, that is, chemical nitrogen fixation and the breeding of cereal varieties responsive to high levels of fertilizer application.

At one extreme is the ecologists' view that a "quasi-perpetual" demographic and economic equilibrium is necessary if a global catastrophe is to be averted (Hardin 1994). At the other extreme is the view of the African Academy of Sciences (1993) that the potential for "transforming" the resources available to humanity is not necessarily finite, so that no limit can be assigned to demographic or economic growth; this represents a touching expression of faith in the power of science and technology from the continent in which these forces have had the least impact. An intermediate view is more plausible: physical limits to growth exist, but they are elastic and can be forced upward by applying increasing techno-economic pressure. The question then arises: Is it reasonable to assume that the pressure can be increased indefinitely? The answer must be no, because it is practically certain that the conditions necessary to maintain economic growth will not last indefinitely. Their disappearance may be brought about by changes in the terrestrial environment or by cultural changes that prompt societies to give higher priority to other objectives. Another possibility, envisaged by Fred Hoyle (1963), is global organizational breakdown occasioned by overpopulation.

United Nations demographers have computed a projection based on the assumption that the fertility rate in each major region will remain at the 1985–90 level. The result of constant fertility combined with a slow but steady increase in the expectation of life at birth would be a world population of 21 billion in 2050, 109 billion in 2100, and 694 billion in 2150. "To many, these data would show very clearly that it is impossible for world fertility levels to remain at current levels for a long time in the future, particularly under assumptions of continuing mortality improvement" (United Nations 1992: 22). If this growth rate continued, it would result in a population density on the world's land surface equal to that of Manhattan (30,000 per square kilometer) by 2200, and "standing room only" (4 persons per square meter) by 2330.

The WEC report points out that "population forecasting has long been a hazardous business, and the past two centuries are littered with erroneous forecasts. But most of the errors have been due to underestimating population growth" (WEC 1993: 44). As a striking example, the English social philosopher Michael Roberts thought that "[w]ithin a century or so, the world's population will almost certainly be stabilized at something like three thousand millions, which is the utmost that the earth is likely to be able to feed" (Roberts 1951: 138). Roberts's error arose from his ecologically inspired belief that chemical fertilizers cannot increase crop yields on a sustainable basis. In addition, he failed to account for the difference between average per capita food consumption in 1948 and the consumption level that would lower population growth to zero because of rising mortality. Even had there been no Green Revolution, world population could still have increased to at least 4 billion before stabilizing.

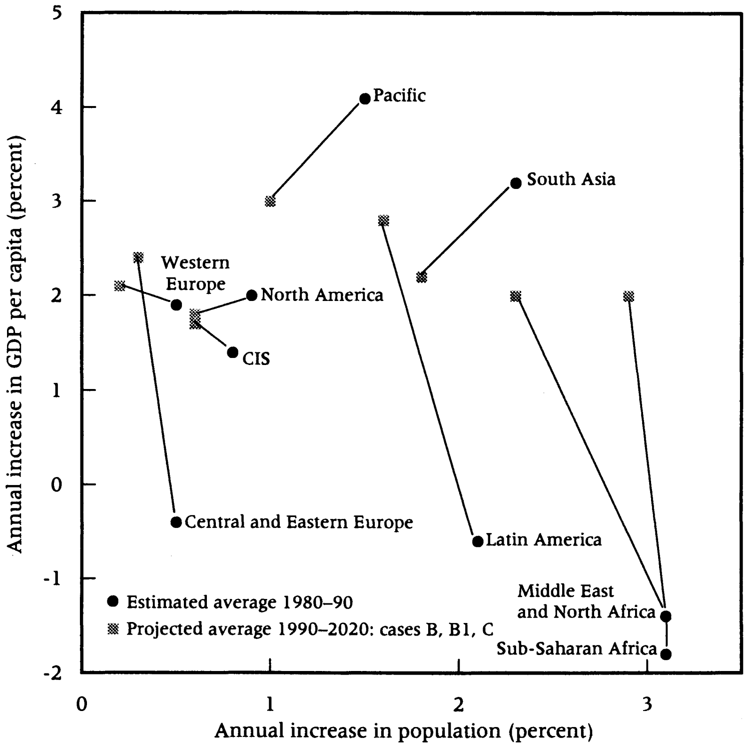
According to the WEC report, "Official projections of global population could easily be out by 10% by 2020, and 30% (perhaps even 50%) by 2100" (WEC 1993: 83). Nevertheless, a long-range global projection can be surprisingly accurate: The 1957 UN "medium" projection for world population in 2000 was 6,267 million (UN 1958); the 1992 revision is 6,228 million (UN 1993).

It is reasonable to conclude that the UN and World Energy Council "medium" projections for world population are more likely than their respective "high" or "low" variants, even though they are based on the highly implausible assumption that fertility in all countries will be at replacement level long before the end of the twenty-first century. Overestimates for some regions will probably be balanced by underestimates for others.

Economic growth

The underlying economic assumptions of the WEC projections and the supplementary projections presented here are that economic growth will continue in all major regions throughout the twenty-first century; that eco-

FIGURE 2 Annual increase in gross domestic product (GDP) per capita and in population: Estimates for 1980–90 and projections for 1990–2020, by world region



SOURCE: WEC 1993

nomic growth rates in the less developed countries will exceed those in the more developed countries; and that economic growth rates will exceed population growth rates in all regions. It is, of course, possible that these assumptions will not hold, but to make other assumptions would stipulate arbitrary reversals of the trend since the 1950s. Furthermore, it would be naive to assume that the people of any country, even the wealthiest, would willingly accept an annual reduction in purchasing power simply because a reduction may be forced upon them at some indeterminate future time. Even those who accept that economic equilibrium or decline is inevitable sooner or later would presumably prefer it to be later.

Figure 2 shows rates of growth of gross domestic product (GDP) per capita and population in each of the nine WEC regions in 1980–90, and the corresponding WEC Case B, B1, and C projections for 1990–2020. (Case B is the base case or reference scenario.)

For a given rate of GDP growth, the rate of growth of GDP per capita will obviously vary inversely with the rate of population growth. It does not follow, however, that growth of GDP per capita would necessarily be accelerated by a decrease in the rate of population growth. Nevertheless, based on a variety of economic arguments, it is commonly expected that there is a negative correlation between growth of GDP per capita and population growth. As Figure 2 shows, the correlation is negative, but it is not very high. Furthermore, for reasons that have not been elucidated, the negative correlation did not appear until the 1980s.

The WEC assumes that the 1990–2020 rate of GDP growth in the MDCs will be 2.4 percent. Two values are adopted for the LDCs: 5.6 percent in Case A (the "high" variant) and 4.6 percent in Cases B, B1, and C. I will supplement these values by "high" and "low" variants for the MDCs and a "low" variant for the LDCs.

It is reasonable to adopt 2.8 percent and 2.0 percent for the "high" and "low" MDC rates, and 3.6 percent for the "low" LDC rate. Economist George Stolnitz holds that there are "mounting indications that the third quarter of this century will turn out to have been a one-time, relatively 'golden' age of productivity uptrends, income advances, and foreign trade expansions in many developed and newly developing nations," and that "numerous unrepayable third world debt situations" have an unfavorable effect on prospects for private sector capital flows to the most capital-starved parts of the world (Stolnitz 1992: 178). If such evaluations prove to be correct, GDP growth rates could be even lower than the "low" values given above.

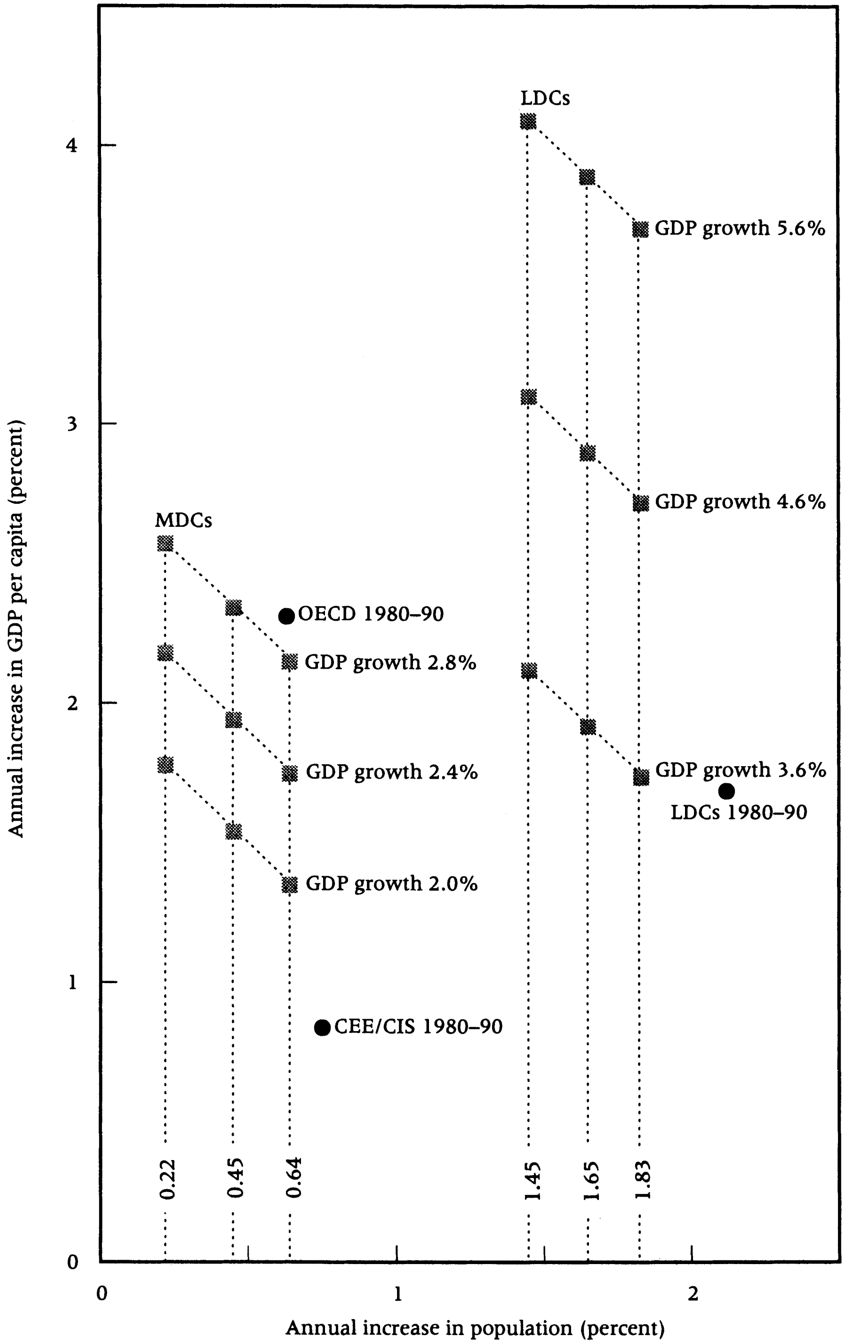
The OECD Secretariat considers an average economic growth rate in the range 2.5–3.0 percent as the most likely scenario for the OECD countries in the period 1995–2000, and contends that a growth rate exceeding 2.5 percent is necessary if a reduction in unemployment is to be achieved (OECD 1994).

Each of the three GDP growth rates can be combined with each of the three population growth rates to give nine variants for growth of GDP per capita in the MDCs and nine in the LDCs. These are shown in Figure 3. For the combination LH–HL (low population growth and high GDP growth in the MDCs, the reverse in the LDCs), the ratio of GDP per capita in the MDCs to that in the LDCs—approximately 7 in 1990 according to WEC data—would rise to 9 in 2020; for the combination HL–LH it would decline to 3. The middle combination, MM–MM, would result in a decline to 5. A GDP growth rate of 3.6 percent in the LDCs and 2.4 percent in the MDCs would leave the ratio unchanged (assuming the same population growth variant for both).

Energy intensity

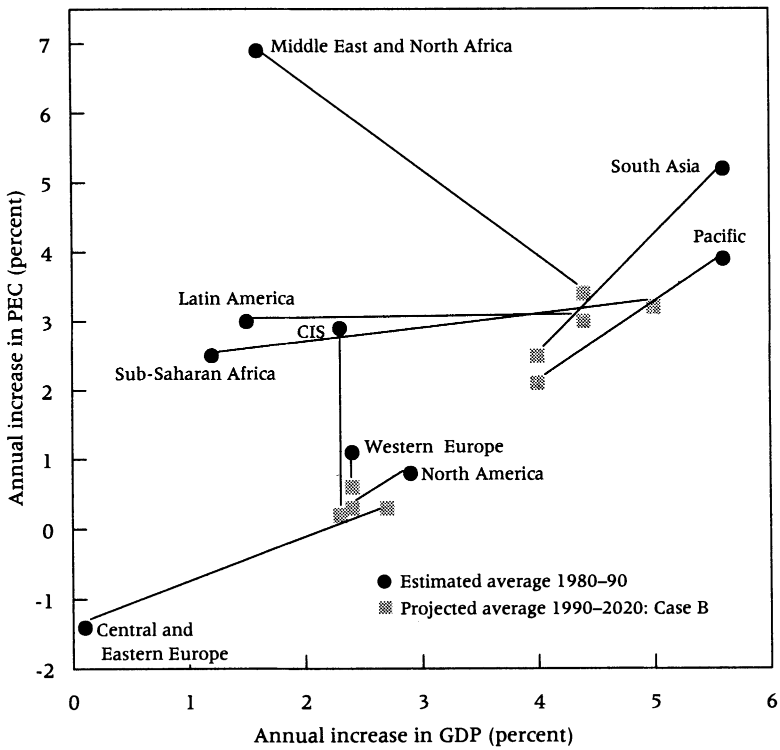
Energy intensity (EI) is defined as primary energy consumption (PEC) per unit of gross domestic product. Future PEC in a region is estimated by the

FIGURE 3 Projected annual increases in GDP per capita under alternative assumptions as to the rate of population growth and the rate of growth in GDP: MDCs and LDCs, 1990–2020. Also shown are 1980–90 estimated values of these variables for three country groupings.



SOURCES: WEC 1993; UN 1993; text

FIGURE 4 Annual increase in primary energy consumption (PEC) and in GDP: Estimates for 1980–90 and projections for 1990–2020, by world region



SOURCE: WEC 1993

WEC on the basis of an assumed rate of GDP growth and an assumed rate of change of EI. For example, if the GDP growth rate is 2.4 percent and the rate of change in EI is –2.0 percent, the PEC growth rate is

$$\frac{1.024}{1.020} - 1 = .0039\,,$$

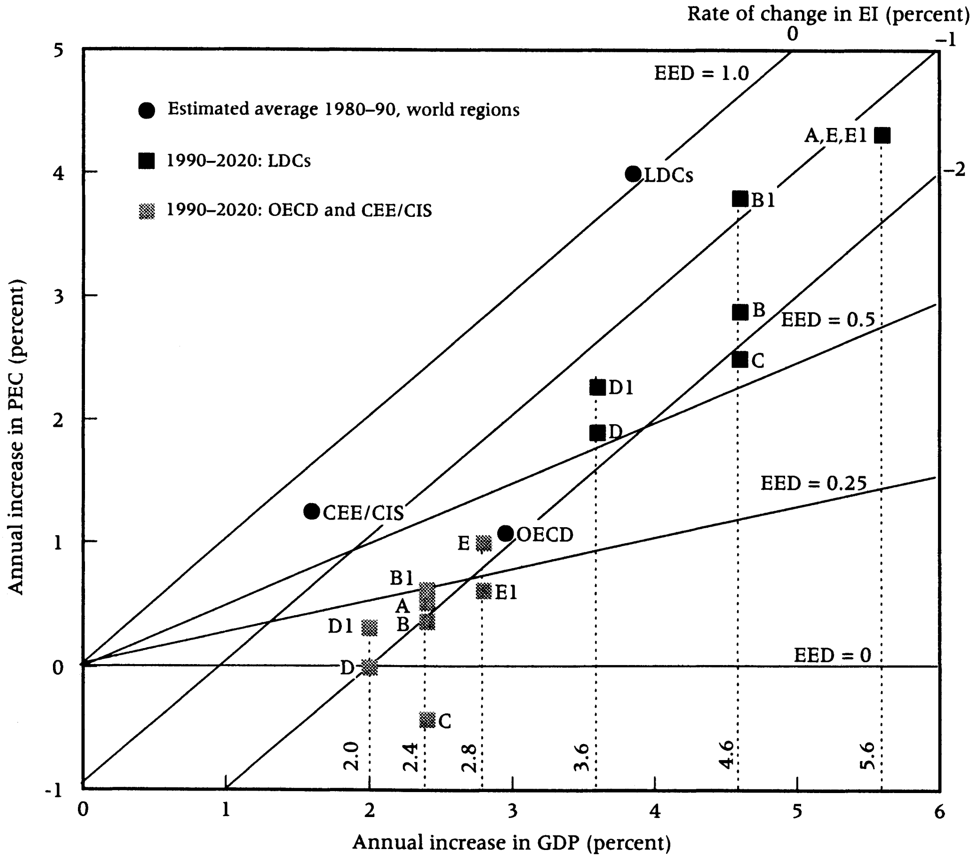
or 0.39 percent.

An alternative method is to use the elasticity of energy demand (EED) instead of the rate of change in EI. EED is defined as the ratio of PEC growth to GDP growth. For example, if the GDP growth rate is 2.4 percent and the EED is 0.16, the PEC growth rate is $0.024 \times 0.16 = 0.0038$, or 0.38 percent.

PEC and GDP growth rates in 1980–90 in each of the nine WEC regions, and the Case B projections for 1990–2020, are shown in Figure 4.

The GDP growth rate, the PEC growth rate, the rate of change in EI, and the EED are by definition interrelated; the values of any two deter-

FIGURE 5 Average annual rates of increase in GDP and in primary energy consumption (PEC), and isoquants for specified values of the rate of change in energy intensity (EI) and of the elasticity of energy demand (EED): Estimates for 1980–90 and projections for 1990–2020 under alternative scenarios



NOTE: Scenarios A, B, B1, and C stipulated by the World Energy Council
SOURCES: WEC 1993 and author's calculations; see discussion in text.

mine the values of the remaining two (except that a zero rate of change in EI implies an EED of 1.0 and is compatible with any value of GDP or PEC growth). Values of the four parameters for each of the three primary country groups in 1980–90 are shown in Figure 5. The four WEC scenarios for 1990–2020 are also shown; the OECD and CEE/CIS have been combined to form one group.

Case A is based on rapid economic growth in the developing countries. Case B assumes a moderate rate of GDP growth. Case B1 is based on a lower rate of EI decline in the CEE/CIS and the LDCs. Case C is the "ecologically driven" scenario, in which very high rates of EI decline are assumed in all regions.

Rising oil and natural gas prices would accelerate the rate of decline in EI or slow the rate of GDP growth in the importing countries. The International Energy Agency predicts that the price of crude petroleum (in constant dollars) will rise from US$17 per barrel (bbl) in 1995 to $28/bbl in 2010 (IEA 1994). The Institut Français du Pétrole predicted in 1993 that the extraction cost from land-based rigs will decline from $8/bbl to $6 in the long term; from offshore rigs from $12 to $8; from deep-sea rigs from $30 to $15. Oil prices can rise while extraction costs fall because the former are determined by supply and demand. Tax revenues from the sale of petroleum products in the oil-importing MDCs now greatly exceed the cost of the products; for example, the price of gasoline at filling stations in Denmark is eight times the import cost including freight. This situation may lead to efforts by producers to secure a larger share of the price paid by consumers, and thus to a rise in prices.

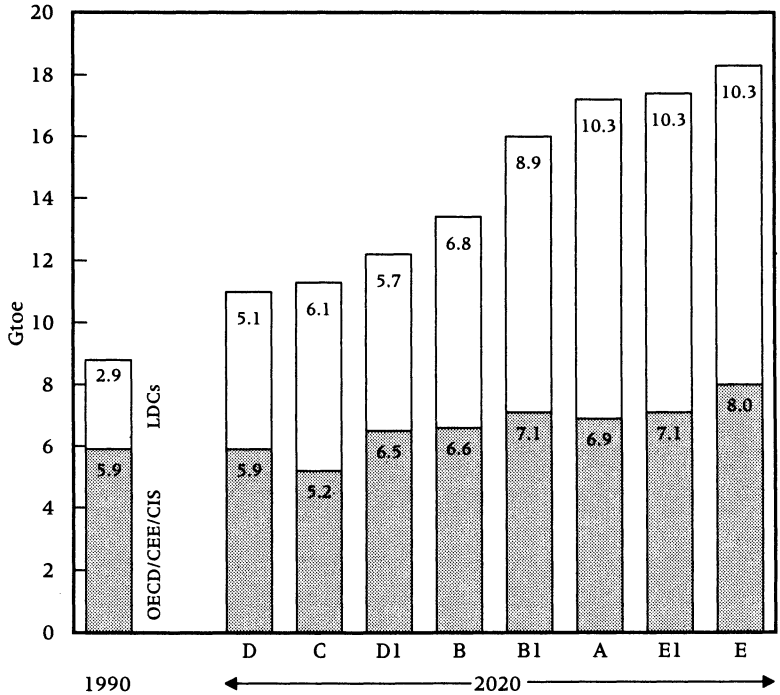
The WEC scenarios need to be supplemented by a low-growth scenario in which the GDP growth rates in the OECD/CEE/CIS and the developing countries are 2.0 percent and 3.6 percent respectively, and a high-growth scenario in which the growth rates are 2.8 percent and 5.6 percent respectively. They are shown as scenarios D, D1, E, and E1 in Figure 5. For scenarios D and E, rates of energy intensity decline equal to those of B and A respectively have been assumed. For scenarios D1 and E1, elasticity of energy demand values equal to those of scenarios B and A respectively have been assumed.

Energy consumption in 2020

The WEC and the supplementary projections for primary energy consumption in 2020 are shown in Figure 6. They have been calculated by applying the assumed rates of change in gross domestic product and energy intensity to the 1990 primary energy consumption, also shown in the figure.

The International Atomic Energy Agency (IAEA) has published "high" and "low" projections for primary energy consumption in the years 2000, 2005, 2010, and 2015 (IAEA 1993). The projections are based on "a compromise among the national projections supplied by each country for a recent OECD/NEA study, the indicators of development published by the World Bank in its World Development Report of 1992, and the estimates of energy, electricity, and nuclear power growth continuously carried out by the International Atomic Energy Agency" (p. 6). The projections can be extrapolated to 2020 by assuming that the 2010–15 trend continues linearly. The "high" projection for 2020 is then 14.0 gigatons of oil equivalent (Gtoe), the "low" 12.5 Gtoe. The mean of the two figures, 13.25 Gtoe, is close to the WEC Case B figure of 13.4 Gtoe. The IAEA projections ex-

FIGURE 6 Primary energy consumption (PEC) in gigatons of oil equivalent (Gtoe): Estimates for 1990 and projected figures in 2020 under alternative scenarios, by world regions



NOTE: Scenarios A, B, B1, and C stipulated by the World Energy Council
SOURCES: WEC 1993 and author's calculations; see discussion in text

clude noncommercial fuels, but use a higher value for world oil consumption than the value adopted by the WEC; the difference between the base-year PECs is small.

The IAEA does not give separate projections for the OECD countries or for the MDCs, but the mean of the extrapolated IAEA "high" and "low" projections for North America, Western Europe, and CEE/CIS is 5.9 Gtoe, identical with the WEC Case B projection for these regions.

In an earlier article, I developed a projection for world energy consumption in 2020 (Gilland 1988). The projection includes fossil fuels, nuclear energy, and hydroelectricity, but excludes biomass. The underlying assumptions include GDP growth rates of 2.0 percent in the MDCs, 4.0 percent in China, and 3.0 percent in all other countries. A value of 1.2 for elasticity of energy demand in the LDCs (excluding China) was used. The result was an energy consumption of 13.15 Gtoe, with the MDCs accounting for 7.67 Gtoe.

I now investigate the sources of the projected energy supply. The breakdown of world primary energy consumption in 1990, by sources, is given in Table 2. The following sections discuss the WEC estimates for each energy source. The projections for PEC by sources are shown in Figure 7.

Renewable energy

The WEC considers renewable energy sources under three headings:

1 Hydroelectricity.

2 Traditional biomass (fuelwood, crop residues, dung).

3 "New" renewables (alcohol, bagasse, biogas, geothermal, small hydro, solar, wind, and ocean thermal).

The projected contributions of these classes of energy source to PEC in 2020 are shown in Table 3.

In Case B, considered the most likely outcome, renewable energy will provide 2.8 Gtoe. With higher total energy demand (Cases A and B1), it will provide 3.1 Gtoe; with strong government support for "new" renewable sources, it will also provide 3.1 Gtoe because the contributions from hydro and traditional sources are assumed to be lower than in the other Cases.

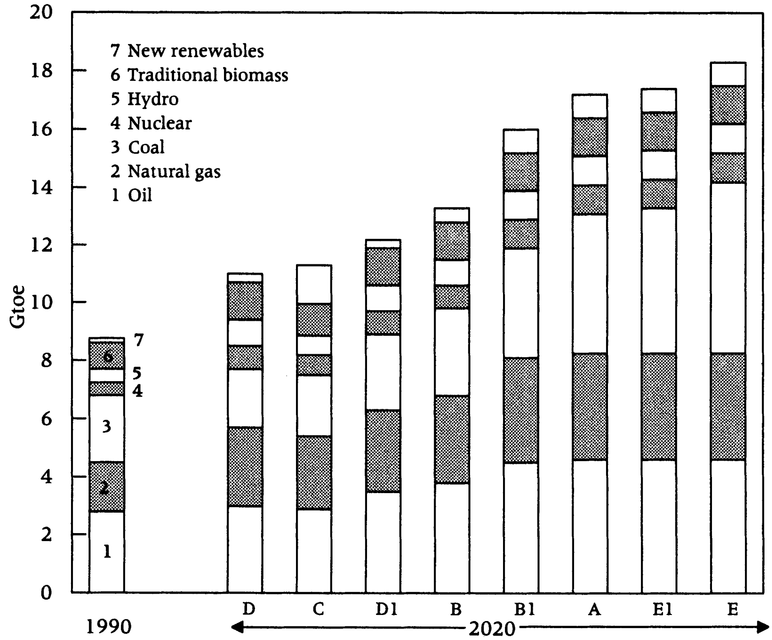
After more than 100 years of development, hydropower reached the annual level of 0.46 Gtoe. After 40 years of development, nuclear reached 0.44 Gtoe. It is therefore unlikely that the annual contribution of the new

TABLE 2 World primary energy consumption: Million tons of oil equivalent (Mtoe), 1990

Energy source		
Fossil fuels		6,810
Oil	2,773	
Coal and lignite	2,319	
Natural gas	1,718	
Renewable energy		1,560
"Traditional" biomass	930	
Large hydroelectric plants	464	
"Modern" biomass	120	
Small hydroelectric plants	20	
Solar	12	
Geothermal	12	
Wind	2	
Nuclear energy		441
Total primary energy		8,811

SOURCE: WEC 1993.

FIGURE 7 Primary energy consumption (PEC) in gigatons of oil equivalent (Gtoe): Estimates for 1990 and projected figures in 2020 under alternative scenarios, by source of energy



NOTE: Scenarios A, B, B1, and C stipulated by the World Energy Council
SOURCES: WEC 1993; text

renewables will increase from 0.16 to 1.35 Gtoe in 30 years. The Case B estimate for the new renewables—0.54 Gtoe—is much more plausible.

Nuclear energy

The contribution of nuclear energy in 2020 is estimated by the WEC at 0.98 Gtoe in Cases A and B1, 0.79 Gtoe in Case B, and 0.69 Gtoe in Case C. As total electricity consumption in Case B is 23,000 TWh (5.13 Gtoe), nuclear energy is projected to provide 15 percent of world electricity in 2020, compared with 17 percent in 1990.

The WEC projections for nuclear energy can be compared with those of the International Atomic Energy Agency. By extrapolating the IAEA projections for 2015 on the assumption that the 2010–15 trend continues linearly, we obtain a "high" estimate of 0.91 Gtoe and a "low" estimate of 0.52 Gtoe for 2020. The "high" estimate reflects "a moderate revival of nuclear power development that could occur in light of a more compre-

TABLE 3 Projections for nonfossil energy consumption in 2020 under 8 different scenarios: Gigatons of oil equivalent (Gtoe)

Energy source	A	B1	B	C
Hydroelectricity	1.00	0.99	0.92	0.66
Traditional biomass	1.32	1.32	1.32	1.06
New renewables	0.81	0.81	0.54	1.35
Nuclear	0.98	0.98	0.79	0.69
Total	4.11	4.10	3.57	3.76
	E	**E1**	**D1**	**D**
Hydroelectricity	1.0	1.0	0.9	0.9
Traditional biomass	1.3	1.3	1.3	1.3
New renewables	0.8	0.8	0.3	0.3
Nuclear	1.0	1.0	0.8	0.8
Total	4.1	4.1	3.3	3.3

SOURCE: WEC 1993; for a description of the scenarios see text.

hensive assessment of the macroeconomic and environmental impacts of the different options available for electricity generation"; the "low" estimate reflects "a continuation of the present trend of nuclear power development stagnation due to public opposition and slowly increasing electricity demand in OECD countries, institutional and socio-political transition in Central and Eastern Europe and lack of funding availability in developing countries" (IAEA 1993: 6).

It has been argued that the "public opposition" to nuclear energy has been created and maintained by groups whose motives are primarily political: "First and foremost, the underlying thrust of the anti-nuclear campaign is not about energy; it is about enmity to technology, industry, profits and free enterprise. Nuclear power is the ideal surrogate target sought out by the coercive collectivists of the intellectual establishment. It is vulnerable to scare campaigns presenting it as mysterious and menacing, and opposing it makes people appear moral—above all to themselves" (Beckmann 1989). But government policy in the former Soviet Union was strongly pro-nuclear; even coercive collectivists cannot arrive at a consensus on this issue.

The opposition to nuclear power plants is ostensibly based on three assumptions:

1 Nuclear reactors are unsafe in operation: To this it must be replied that the risks are far lower than many that are accepted without question. A. Scargill, president of the National Union of Mineworkers (UK), stated at a public inquiry that he would be reconciled to nuclear energy if it could be proved that not one person would ever be killed by the use of nuclear

power (Fremlin 1989: 300). This is a remarkable statement from a representative of an industry that costs the lives of 11,000 miners per year in accidents worldwide (ILO 1995). To demand zero risk is to demand the cessation of all human activity.

2 Nuclear reactors produce radioactive waste that cannot be disposed of safely: A political solution for the permanent disposal of high-level waste will have to be found, as several thousand tons of it exist and cannot be stored in steel tanks indefinitely. Once a solution has been found, disposing of additional amounts should present no special problem. The problem is basically one of overcoming the NIMBY (Not in My Back Yard) syndrome when designating a location for a waste depository. The technical problem was solved long ago.

3 The plutonium in the spent fuel from nuclear reactors can be extracted and used for nuclear weapons; the greater the number of reactors, the greater the risk of nuclear weapons proliferation: To produce a plutonium bomb requires not only a reactor, but also a nuclear fuel reprocessing plant and a supply of spent fuel that has been prematurely removed from a reactor, that is, removed before more than a small fraction of the fissile plutonium (Pu-239) has been transformed to nonfissile isotopes (mainly Pu-240). The risk of weapons-grade plutonium being produced in contravention of the Non-Proliferation Treaty is minimized by international inspection of nuclear installations. But even the closing down of all reactors could not prevent a country with adequate engineering resources from building a uranium (U-235) bomb if it wished to do so. All that is necessary is a supply of natural uranium (which contains 0.7 percent U-235) and an isotope-separating plant. Each of the five openly nuclear weapons states tested its first bomb long before its first nuclear power plant was commissioned.

The WEC takes a more optimistic view of the future of nuclear energy in the medium term than does the IAEA; even the "ecologically driven" Case C is based on a higher nuclear contribution than the extrapolated IAEA "low" projection.

Fossil fuels

The WEC and the supplementary projections for coal, oil, and natural gas consumption in 2020 are shown in Table 4. It can be seen that the Case A projections for oil and natural gas are considered to be close to the practical limit.

The very large increases in coal consumption assumed in Cases A, E, and E1 make these projections implausible. A continuation of the 1982–89 trend to 2020 would result in a coal consumption of 3.6 Gtoe. Coal consumption peaked at 2.26 Gtoe in 1989 and declined to 2.15 Gtoe in 1994 (BP 1995).

TABLE 4 Projections for fossil energy consumption in 2020 under 8 different scenarios: Gigatons of oil equivalent (Gtoe)

Energy source	A	B1	B	C
Coal	4.85	3.8	3.0	2.1
Oil	4.6	4.5	3.8	2.9
Natural gas	3.65	3.6	3.0	2.5
Total	13.1	11.9	9.8	7.5
	E	**E1**	**D1**	**D**
Coal	5.95	5.05	2.6	2.0
Oil	4.6	4.6	3.5	3.0
Natural gas	3.65	3.65	2.8	2.7
Total	14.2	13.3	8.9	7.7

SOURCE: WEC 1993; for a description of the scenarios see text.

Energy consumption in 2100

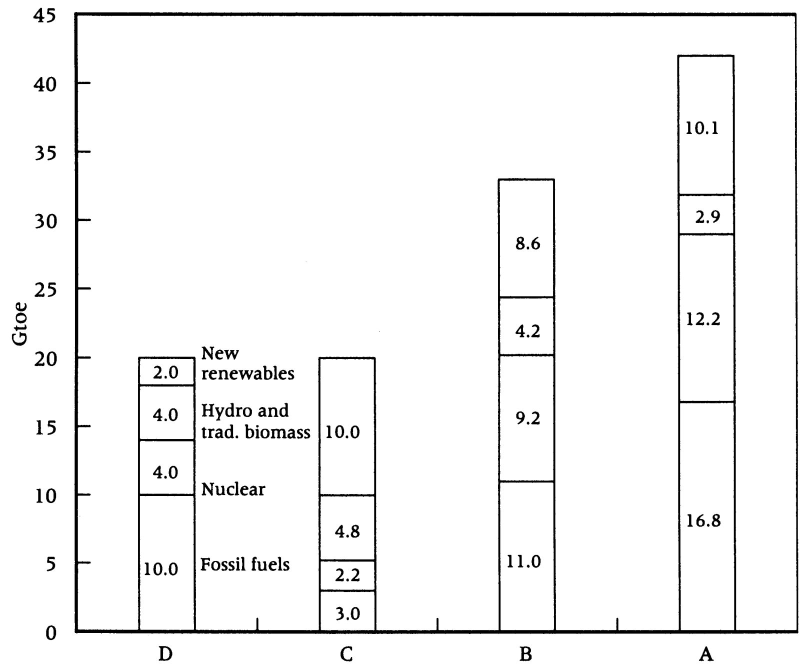
The WEC report includes illustrative extensions of Cases A, B, and C to the year 2100. The energy sources are classed in four groups: fossil fuels, nuclear, hydroelectricity and traditional biomass, and new renewables. The projections for 2100 are shown in Figure 8, together with an extension of Case D. To assess the plausibility of the WEC projections, I consider the developable potentials of each of the four categories of energy source in the period up to 2100.

Fossil fuels

The WEC gives the proved reserves of coal and lignite in 1990 as 606 Gtoe, and of oil and natural gas as 245 Gtoe. The corresponding figures for "ultimately recoverable resources" are 3,400 and 1,000 Gtoe respectively.

The maximum estimate for the recoverable reserves of oil and natural gas is 1,000 Gtoe. The cumulative consumption of oil and natural gas from the sinking of the first oil wells in 1857 up to 1990 is estimated at 126 Gtoe (WEC 1993). The total amount that will be recovered from 1857 to the exhaustion of the reserves will therefore be taken as 1,126 Gtoe. By assuming that the consumption curve will be symmetrical about its peak, that is, that the cumulative consumption will be 563 Gtoe prior to reaching the peak and 563 Gtoe from the peak to the exhaustion of the reserves, oil and natural gas consumption can be extrapolated to 2100. These extrapolations are shown in Figure 9. (Case C is not shown, as it is assumed in that projection that consumption reaches zero before the reserves are exhausted.)

FIGURE 8 Projected global primary energy consumption (PEC) in gigatons of oil equivalent (Gtoe) by source in 2100 according to alternative scenarios



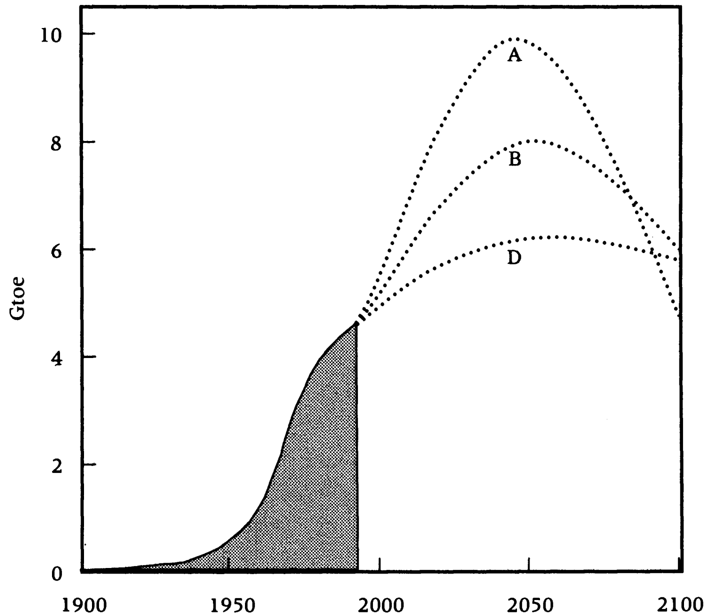
SOURCE: WEC 1993; see discussion in text

It is clear from Figure 9 that oil and natural gas consumption cannot be expected to exceed 6 Gtoe in 2100. (If exploitation of the 400 Gtoe of shale oil—included in the 1,000 Gtoe estimate—proves uneconomic or environmentally unacceptable, consumption would be considerably lower.) It is difficult to believe that coal and lignite will provide much more than 5 Gtoe (7 billion tons of coal equivalent) in 2100, although Frisch has projected 6.5 Gtoe in 2060 (Frisch 1986). A plausible—and fairly optimistic—estimate for fossil fuel consumption in 2100 is 10 Gtoe, of which roughly half is provided by coal and lignite. This is close to the extension of Case B, and is incorporated in the extension of Case D.

Nuclear energy

The maximum rate of completion of nuclear power plants worldwide in the next few decades is unlikely to exceed 60 GWe of electrical generating capacity per year. (The French average in 1982–92 was 4 GWe per year; the world's nuclear construction capability can be estimated at roughly 15 times that of France.) The design service life of a reactor is currently 40

FIGURE 9 Estimated global consumption of oil and natural gas in gigatons of oil equivalent (Gtoe), 1900–90, and projections for 1990–2100



SOURCE: See discussion in text

years, but the target service life of the next generation of reactors, under development by Framatome and Siemens, is 60 years. If it is assumed that the service life will rise to 60 years and thereafter remain at that figure, and that the construction rate averages 60 GWe per year, the maximum nuclear generating capacity attainable in 2100 would be 3,600 GWe.

A power plant of 1 GWe generating capacity, operating at a load-factor of 75 percent (typical for nuclear plants), produces 6.57 TWh of electricity per year. This corresponds to 1.46 Mtoe of primary energy. A nuclear capacity of 3,600 GWe would thus provide 5.3 Gtoe per year.

Because of uranium supply limits, a rapidly increasing proportion of the reactors built after world nuclear capacity passes 1,000 GWe will have to be fast breeder reactors (FBRs), which can produce at least 50 times (theoretically, up to 100 times) as much energy from a given amount of natural uranium as thermal reactors.[2] The construction cost per MWe of an FBR is much higher than that of a thermal reactor; although the cost will diminish, an appreciable cost difference between the two reactor types will remain.

Four FBRs are in operation in the former Soviet Union, two in France, and one in Japan; two are under construction in the Russian Federation. A prototype FBR is at the design stage in India, and China has announced its intention to construct an experimental FBR (IAEA 1994). The British prototype FBR was shut down in 1994 after 19 years of operation. The German FBR is to be dismantled after the government of North Rhine-Westphalia refused to issue an operating permit for political reasons. Plans for the Clinch River (Tennessee) FBR were abandoned in the 1980s.

If the fusion of deuterium and lithium nuclei can be made to yield a net energy gain, fusion reactors will become feasible. It is unlikely that the deployment of fusion reactors can be sufficiently rapid to make the fast breeder reactor superfluous, but it is possible that fusion reactors will be used for converting uranium-238 to plutonium-239 for fueling thermal reactors, further reducing the need for FBRs.

The International Thermonuclear Experimental Reactor (ITER) project, launched in 1988, is aimed at demonstrating the feasibility of controlled nuclear fusion. It is intended to produce a design for a reactor capable of sustaining fusion in a magnetically confined deuterium-tritium plasma for 1,000 seconds. If the reactor is eventually built, it may be followed by a commercial prototype around 2025 (Butler 1994). If ITER fails, funding for fusion research—currently at $1.5 billion per year—will be drastically reduced (Butler 1994).

In this presentation I will take the maximum achievable nuclear generating capacity in 2100 as 2,500 GWe, corresponding to 3.7 Gtoe of primary energy. The nuclear contributions in Cases A and B must be considered highly unrealistic.[3]

Hydroelectricity and traditional biomass

The energy dissipated annually by the world's rivers is approximately 80,000 TWh. About 15 percent of it could be harnessed; the developable hydropower potential of 12,000 TWh corresponds to 2.7 Gtoe per year (WEC 1977). Although it is practically certain that the entire potential will never be developed, between half and two-thirds will likely be developed by 2100.[4]

The theoretical maximum sustainable production of the world's forests has been estimated at 5.4 billion tons of dry wood per year (Windhorst 1979). This corresponds to 2.2 Gtoe per year. Burning crop residues (chiefly straw) as fuel could ultimately provide an additional 1 to 1.5 Gtoe per year.

The total production of this group of energy sources is thus very unlikely to exceed the Case C figure of 4.8 Gtoe in 2100. The Case B figure of 4.2 Gtoe is more plausible.

New renewable energy sources

The theoretical potential of solar energy, that is, the conversion to electricity of solar radiation incident on the Earth's surface, is far greater than the potentials of all the other energy sources in this category combined (Nitsch 1994). As this article is not a comprehensive review of energy technologies, the discussion of new renewable energy sources is confined to solar energy.

The areas suitable for solar power plants are level, stony deserts in the arid tropics. These areas total 1.9 million square kilometers, two-thirds of them in North Africa and the Middle East (Nitsch 1994). The mean insolation in the arid tropics is 250 W/m^2; the global average is 160 W/m^2.

Solar chimneys could be used to collect energy on very large areas. A solar chimney consists of a circular array of glass panels with a chimney at the center. The air under the panels is heated by the sun (the greenhouse effect) and flows from the periphery to the center and up the chimney, in which wind turbines are installed. With double glazing and a chimney 1,500 meters (m) high, an efficiency of 2.4 percent is attainable (Schlaich 1994). An installation 5 km in diameter would produce an average power of 120 megawatts (MW), or 0.23 Mtoe per year.

If the solar energy incident on the entire 1.9 million km^2 were converted at 2.4 percent efficiency, production of solar electricity would be 100,000 TWh, or 22 Gtoe of primary energy. Using a different method of calculation, Nitsch estimates the solar potential at 20 Gtoe (Nitsch 1994). If solar chimneys were the sole type of conversion installation, it would be necessary to double-glaze an area almost three times the size of Texas and to build 100,000 chimneys, each almost four times the height of the buildings of the New York World Trade Center. Clearly this is a task that would have to extend over several hundred years.

A solar chimney with 14,000 m^2 of panels and a 200 m chimney was built in Spain, operated from 1983 to 1989, and subsequently dismantled. Its average power was 5 kW, in agreement with the calculated value (Schlaich 1994).

The WEC considers that "solar systems are not as well adapted to concentrated urban uses as more dispersed uses, and attempts to overcome this problem with huge parabolic mirrors and solar chimneys (which are not the main thrust of recent developments or current prospects) should be avoided" (WEC 1993: 96).

The prospect for solar chimneys is not bright, and large-scale solar power production, if it becomes feasible, is almost certain to be based on a different principle from the one described above. One possibility is the aeroelectric tower, invented by Phillip Carlson in 1965 and currently under investigation at the Israel Institute of Technology. Whereas the solar chimney generates an upward flow of heated air, the aeroelectric tower generates a downward flow of cooled air. The air is cooled by the evaporation of seawater, pumped to the top of the tower, and sprayed through atomizers. It has been calculated that a tower 1,000 m high and 500 m in diameter would produce an average power of 450 MW. As the heat of vaporization of water at 30° C is 675 kWh per metric ton, and the overall efficiency is 0.9 percent, the net electrical output would be 6 kWh per cubic meter of water, and the annual water consumption of a 450 MW installation would be approximately 650 million cubic meters. If the capital cost of such an installation were $1 billion, the electricity produced would cost 3 cents per kWh (excluding the cost of pumping water from the sea to the base of the plant and of pumping brine from the plant to the sea). Whether this optimistic evaluation is realistic remains to be seen. A pilot plant may be in operation by 1997 (Zaslavsky 1994).

Another possibility for large-scale solar electricity generation is the trough collector power plant, in which solar radiation is concentrated on a tube located at the focus of a series of parabolic mirrors. The tube transports a fluid, the heat from which is transferred to a boiler, which supplies steam to a turbine. Several plants of this type have been built in southern California; the largest has a collecting area of 464,000 m^2 and a peak power of 80 MWe. Because the peak power is available only from 8 am to 4 pm from mid-April to mid-August, solar heat is supplemented by natural gas. The annual average output is 29MWe, of which natural gas provides 25 percent. The annual solar electricity output of 410 kWh/m^2 corresponds to a conversion efficiency of approximately 17 percent. The cost per kWh is around 10 cents, almost double that of fossil or nuclear electricity. Another type of solar thermal plant is the power tower, in which sun-tracking mirrors (heliostats) concentrate solar radiation on a receiver located atop a tower. The heat is converted to electricity in the same way as in the parabolic trough plant. A 10 MWe power tower was built in California's Mojave Desert in 1982. It was closed down in 1988 after six years of operation as a research project. The construction cost per installed kilowatt was $14,000, almost five times that of the 80 MWe parabolic trough plant built in the Mojave in 1989.

Photovoltaic conversion of solar energy to electricity is an alternative to the thermal conversion installations described above. When a cell containing a thin disc of crystalline silicon is exposed to sunlight, a direct current of up to one volt is generated with a conversion efficiency of approximately 20 percent. Arrays of photovoltaic cells can be connected to form a power plant, the direct current being transformed to a high-voltage alternating current. The cells are expensive, however, and the rate of cost decline has not been as rapid as expected. Cells that incorporate a thin layer of amorphous silicon are much cheaper, and an efficiency of 10 percent has recently been achieved. Amorphous silicon cells of this efficiency are scheduled to go into commercial production in 1995; the US Department of Energy predicts that they will lower the cost of photovoltaic electricity to 12 to 16 cents per kWh, less than half the current price (Beardsley 1994). A planned 100 MW amorphous silicon cell power plant in Nevada may be in operation by 2005.

The current world demand for increased photovoltaic generating capacity is 70 MW per year, or one forty-thousandth of world electrical generating capacity. The relatively short service life of photovoltaic cells—about 20 years—will have to be increased considerably if they are ever to make a significant contribution to world energy production.

A major disadvantage of the large-scale generation of solar electricity—photovoltaic as well as thermal—without fossil-fuel backup is the need for energy storage. The method usually envisaged—conversion of electricity to hydrogen by electrolysis and reconversion to electricity by fuel cells or gas turbines—is extremely expensive and may never become economical (Gilland 1990).

The ultimate high-technology solar energy system is the power satellite, first suggested by P. E. Glaser in 1968. It consists of an array of photovoltaic cells assembled in space and placed in geosynchronous orbit (a circle with a radius of 42,165 km in the plane of the equator), so that it is stationary relative to any point on Earth. The electrical output of the cells is converted to microwaves, which are beamed to Earth, collected by a receiver (rectifying antenna), and reconverted to electricity. As the cells always face the sun, they would receive 1,370 W/m^2 continuously, over five times the mean insolation at the Earth's surface in the arid tropics. The power output would be uninterrupted for most of the year, but when the Earth is at or near an equinox it eclipses a geosynchronous satellite once per day; the period of eclipse attains a maximum of 70 minutes at the equinox. A 5 GWe satellite would have a mass of at least 30,000 tons. As a space shuttle has a maximum payload of 26 tons to low orbit (up to 400 km from Earth), and a single flight to and from orbit costs $420 million (Robertson 1995), the cost of transporting the satellite components to geosynchronous orbit would exceed $500 billion, and the cost of the electricity would exceed one dollar per kWh.

Because the cost of solar electricity is likely to remain higher than the cost of nuclear or hydroelectricity for a long time to come, the rate of deployment of solar power plants will probably be slow.

A reasonable estimate for energy production from the new renewable sources in 2100 is 2 Gtoe, that is, four times the Case B figure for 2020. The estimates for 2100 in Cases A, B, and C are based on unrealistic "exponential" thinking.

The EPA projection

The US Environmental Protection Agency (EPA) has projected world energy consumption to 2100, using a method similar to that of the WEC (EPA 1990).

The EPA projection is based on three assumptions:

1 The year-2100 populations of the MDCs and LDCs (as these groups of countries are currently defined) will be 1.5 and 9.0 billion respectively.

2 GDP per capita in the MDCs and LDCs will increase at 2 percent and 3 percent per year respectively to $100,000 and $25,000 respectively (in 1988 dollars).

3 Energy intensity in the MDCs and LDCs will decline at approximately 1.4 percent and 1.6 percent per year respectively to 4 MJ/$ in both groups of countries.

The projected energy consumption is 36 Gtoe, in fairly good agreement with the 33 Gtoe of the WEC Case B extension. The sensitivity of the projection to variations in the assumptions can be shown by using 1.5 percent and 2.5 percent for the GDP per capita growth rates, which reduces the projected energy consumption to 20 Gtoe, in agreement with the extensions of Cases C and D.

Carbon dioxide and climate

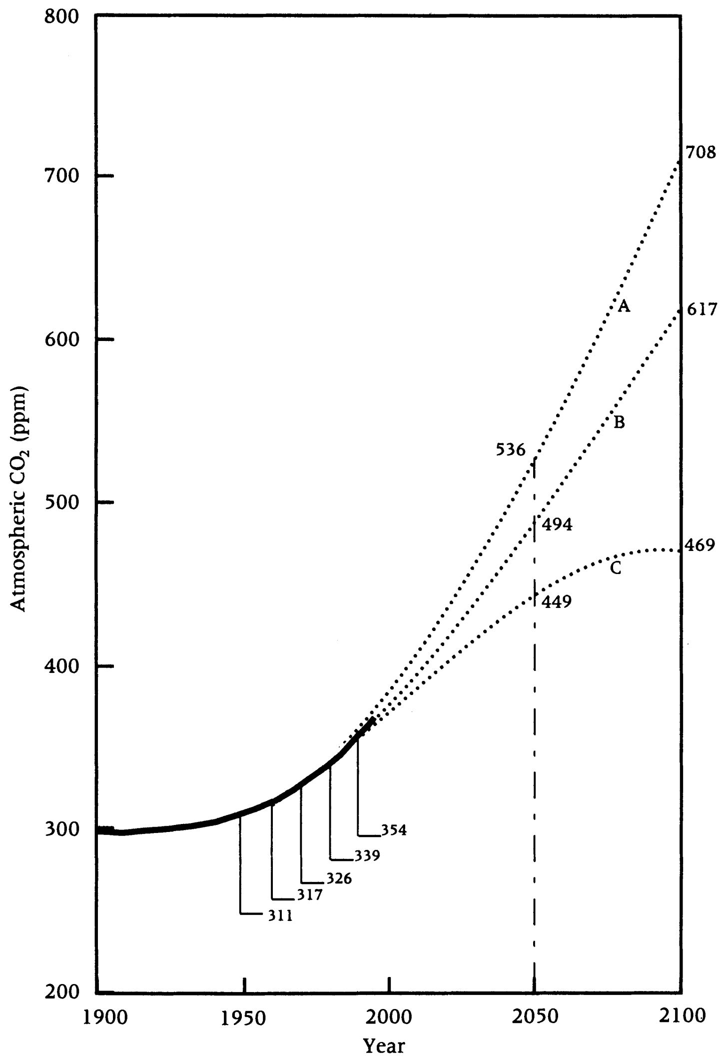
The concentration of carbon dioxide (CO_2) in the atmosphere increased from approximately 280 parts per million by volume (ppm) in 1750 to 354 ppm in 1990, and is now increasing at 1.6 ppm per year. A rising CO_2 concentration will have climatic effects, including a rise in global mean temperature and mean sea level, but the magnitudes of the effects are highly uncertain. As CO_2 emission from fossil fuel combustion is the principal cause of the rise in atmospheric CO_2 concentration, there is widespread concern about the increasing use of fossil energy.

Atmospheric CO_2 concentration in 1900–90 and the WEC illustrative scenarios for 1990–2100 are shown in Figure 10. The relationship between the CO_2 concentration in 2100 and the rise in global mean temperature (relative to 1990), computed at the request of the WEC by T. M. L. Wigley and M. Hulme of the Climate Research Unit of the University of East Anglia, using the MAGICC climate model, is shown in Figure 11. There is a wide margin of uncertainty for each scenario regarding both the CO_2 concentration and the rise in global mean temperature. The uncertainty in CO_2 concentration arises from the uncertainty in the future airborne fraction, the fraction of the CO_2 emission that remains in the atmosphere.

The assumed airborne fraction for each scenario is not stated in the WEC report, but can be calculated from the data given. For Case B, the cumulative carbon emission in 1990–2100 is 1,180 Gt. The atmospheric CO_2 concentration is projected to rise by 262 ppm. As 1 ppm of atmospheric CO_2 has a carbon content of 2.128 Gt, the CO_2 rise corresponds to an additional 558 Gt of carbon in the atmosphere.[5] The assumed mean airborne fraction is thus 558/1,180, or 0.47, which agrees closely with historical estimates.

The temperature rises predicted by the MAGICC and other climate models are purely theoretical; no temperature change that can be ascribed to rising CO_2 concentration has yet been observed.[6] A study of 27,000 tem-

FIGURE 10 Atmospheric carbon dioxide concentration, 1900–90, and projected concentrations under alternative assumptions for 1990–2100

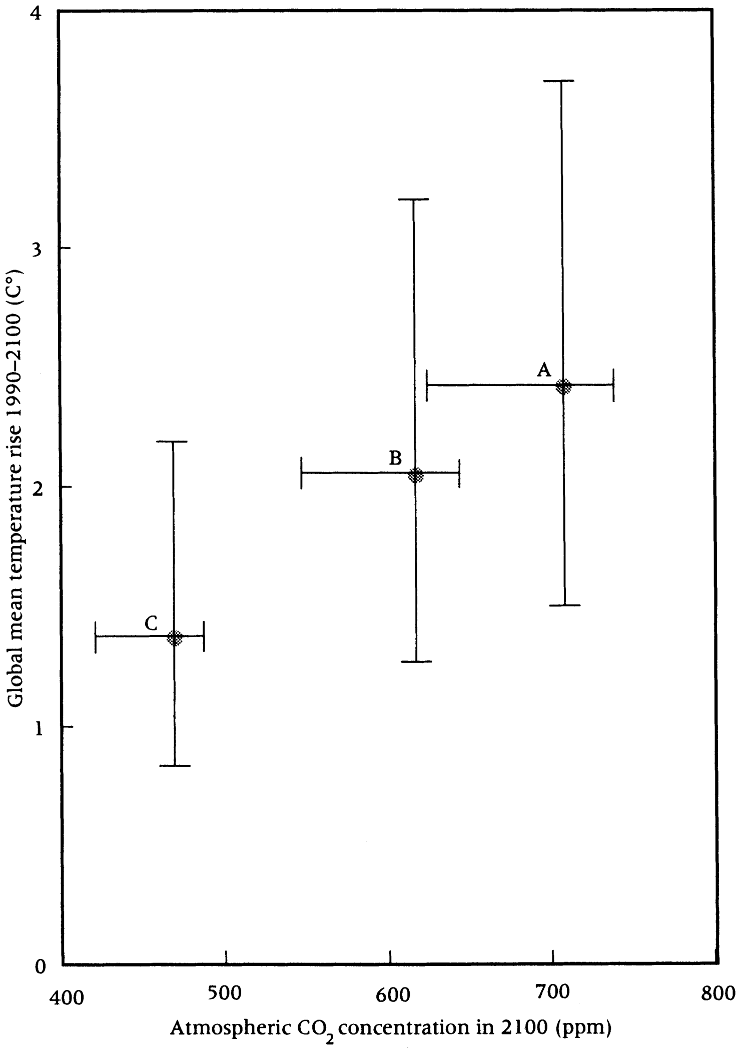


SOURCES: 1900–90: Database of the Hadley Centre for Climate Prediction and Research (Bracknell, England); 2050 and 2100: World Energy Council.

perature profiles over 40 years, reported in January 1993, showed no evidence of surface warming in the Arctic Ocean and a significant temperature decrease in the western part of the ocean between 1950 and 1990 (Allaby 1994).

Figure 12 shows quinquennial average surface air temperatures in Denmark for the period 1875–1994. The data are based on several daily

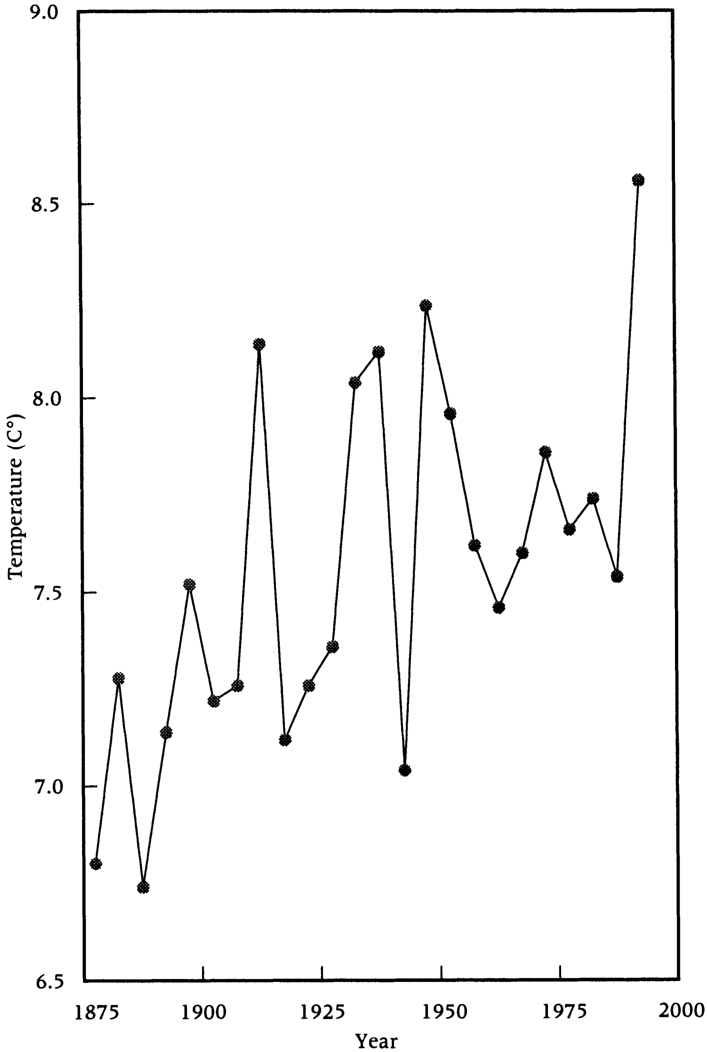
FIGURE 11 Projections for atmospheric carbon dioxide concentration in 2100 under alternative assumptions and estimated high, medium, and low values of corresponding global mean temperature rise for 1990–2100



SOURCE: WEC 1993

readings at about 30 observation stations. The pattern of temperature variation is similar to that for the Northern Hemisphere. It remains to be seen whether the relatively high temperatures observed in 1990–94 are a short-term deviation or the precursor of a warmer period; it would be rash to ascribe it prematurely to the greenhouse effect.[7] During the European heat

FIGURE 12 Quinquennial average surface air temperatures in Denmark, 1875–79 to 1990–94



SOURCE: Database of the Danish Meteorological Institute

wave of July 1994, Klaus Töpfer, then German Minister of the Environment, announced that the greenhouse effect had arrived. Per Stig Møller, a former Danish Minister of the Environment, facetiously commented: "It must have arrived immediately after Midsummer Eve, as the weather had been unusually cold until then" (Møller 1995). Töpfer was subsequently informed that July had been equally warm in 1794, 1797, and 1834.

The WEC report includes an extract from "Climate change 1992: The supplementary report to the IPCC scientific assessment," which mentions increasing evidence of a cooling effect due to sulfate aerosols (airborne particles). This has subsequently been confirmed: "In all probability, aerosols primarily composed of sulfates, themselves the result of commercial activity, enhance the ability of the atmosphere to reflect sunlight back into space before it can reach the planet's surface and participate in the warming process" (Charlson and Wigley 1994).

Anthropogenic sulfur emission, mainly in the form of sulfur dioxide, is estimated by the WEC at 65 million tons in 1990. It is about double the emission from natural sources, mainly dimethyl sulfide from marine phytoplankton. About half the amount of sulfur gases in the atmosphere is either washed out by rain or reacts with plants, soil, and seawater; the remainder is oxidized to aerosol particles. The anthropogenic sulfur emission in 2020 is projected at 98 million tons in Case A, 88 million t in Case B1, 66 million t in Case B, and 43 million t in Case C.

Analysis of ice cores bored in Greenland and Antarctica shows that temperature fluctuations are highly correlated with fluctuations in atmospheric CO_2 concentration. But the temperature rises occur shortly before the CO_2 rises, showing that, if the two are causally connected, the former cause the latter. The explanation is that the oceans contain large amounts of CO_2; when the ocean temperature rises, the solubility of CO_2 declines, and CO_2 is released to the atmosphere.

The change in attitude to man-made changes in the environment (by focusing on anticipated detrimental instead of beneficial effects) is strikingly illustrated by contrasting current concern about the greenhouse effect with the suggestion of biochemist Harrison Brown, that a tripling of the atmospheric CO_2 concentration would allow a doubling of world food production (Brown 1954: 142). Brown considered the absorption of CO_2 by the oceans to be a "serious limitation," going as far as to suggest that CO_2 from fossil fuel combustion be supplemented by heating limestone.

Rises in mean sea level by 2100 were also estimated by using the MAGICC climate model. The results were rises of 48, 42, and 33 cm for Cases A, B, and C respectively. The uncertainty is given for Case B only: a minimum of 12 and a maximum of 81 cm.

The estimated rises in CO_2 concentration, global mean temperature, and mean sea level by 2100 for Case D are obviously slightly lower than those for Case B.

The judgment of the WEC: "Readers are left to draw their own conclusions as to the severity of the challenge the world may face, and the extent of abatement and adaptation measures that may be demanded" (WEC 1993: 310). The WEC would have done better to emphasize that the basis for drawing conclusions on the severity of the challenge is still inadequate.

Conclusions

The considerations advanced in this article point to the following conclusions:

1 The UN "medium" population projection is plausible for the period up to 2020.

2 Plausible scenarios for world primary energy consumption in the year 2020 are WEC Case B (13.4 Gtoe) and the supplementary Case D (11.0 Gtoe). For comparison, world energy consumption in 1990 was 8.8 Gtoe.

3 The ranges of uncertainty in population and energy for the year 2100 are enormous. Nevertheless, it is difficult to see how primary energy consumption in that year can exceed 20 Gtoe, which will probably be just sufficient to maintain the global average at 1.7 tons of oil equivalent per capita. One way of attaining this level of consumption is a 50 percent increase (relative to 1990) in fossil fuel production, combined with a doubling of traditional biomass production, a quadrupling of hydroelectricity production, a ninefold increase in nuclear energy production, and a twelvefold increase in new renewable energy production.

4 The atmospheric CO_2 concentration in 2100 will probably be somewhat lower than the 617 ppm of the WEC Case B extension, but is almost certain to exceed the 469 ppm of the WEC Case C extension. (The concentration in 1990 was 355 ppm.) If the increase in concentration induces unfavorable climate changes, they should be regarded as part of the price to be paid for the fossil energy bonanza that has culminated in the affluent society.

Notes

1 The World Energy Council, founded in 1924, is a nongovernmental, nonpolitical organization with national committees in 99 countries. Its objective is "to promote the sustainable supply and use of energy for the greatest benefit of all." It holds a World Energy Conference triennially; the 15th Conference was held in Madrid in 1992, and the 16th will be held in Tokyo in 1995. The WEC Commission responsible for the report was formed in 1990, and the report was published in September 1993; over 500 people from all five continents participated in its preparation.

2 World reactor capacity at the end of 1994 was 340 GWe; an additional 39 GWe was under construction.

Fueling a pressurized water reactor (the dominant reactor type) of 1 GWe generating capacity, operating at a load factor of 75 percent, requires 149 tons of natural uranium per year on the "once through" fuel cycle, i.e., without reprocessing spent fuel.

Operating reactors with a total capacity of 1,000 GWe for 60 years on this basis would thus require 9 million tons of natural uranium. "Known" uranium resources amount to 3.7 million tons, and "undiscovered" resources are estimated at 13 million tons (WEC 1993: 91).

Uranium (in the form of uranyl tricarbonate) is present in seawater at a concentration of 3 parts per billion; the total amount exceeds 4 billion tons. However, the feasibility of large-scale extraction is highly problematic; cost estimates vary from several hundred to several thousand dollars per kg of uranium. The current price of natural uranium is approximately $60 per kg; an increase of $1,000 per kg would raise the cost of nuclear electricity produced on the "once through" cycle by 2.3 cents per kWh.

The only certain method of extending uranium resources is large-scale deployment of breeder reactors. Whereas a pressurized water reactor fissions less than 900 kg of material per year, i.e., 0.6 percent of the natural uranium required to provide the fuel, a breeder can use up to 60 percent of the natural uranium by converting U-238 in a "blanket" surrounding the reactor to plutonium-239. However, the plutonium in the blanket is weapons-grade. It would therefore probably be necessary to confine plants that reprocess breeder blanket material to a small number of locations under internationally agreed supervision.

3 Goeller and Weinberg envisaged a world of 10 billion people in which energy demand would be met by 15,000 breeder reactors, each of 2 GWe. The total production of thermal energy would be 75 terawatts, or 56 Gtoe per year (Goeller and Weinberg 1976). The authors did not state when they considered this energy system could be deployed, but three years later Goeller wrote that 75 TW "would require an enormous endeavor but would not, in our opinion, be impossible, given a century or more in which to accomplish it." He added that "a twelvefold increase in 150 years represents an average annual growth rate of only 1.7 per cent" (Goeller 1979: 155). Arguably, this is a good example of how "exponential" thinking leads to tenuous conclusions.

4 The annual flow of the world's rivers (39,000 km^3), falling through the mean height of the continents (excluding Antarctica) above sea level (738 m), dissipates 78,000 TWh. In 1988, world hydroelectricity production was 2,100 TWh. The volume of water impounded in reservoirs above dams was 5,500 km^3, and the area of the reservoirs was approximately 350,000 km^2. If hydroelectricity production were increased to 12,000 TWh per year, the reservoir volume and area would be roughly 30,000 km^3 and 2 million km^2 respectively. For comparison, the volume and area of the world's lakes and inland seas are 230,000 km^3 and 2.5 million km^2 respectively.

5 The figure 2.128 is derived as follows:

Mass of the atmosphere = 5.136 million Gt

Molecular weight of CO_2 = 44

Mean molecular weight of air = 28.96

Mass of 1 ppm CO_2 = 5.136(44/28.96)= 7.803 Gt

Atomic weight of carbon = 12

Carbon content of 1 ppm CO_2 = 7.803(12/44)= 2.128 Gt.

6 The European Climate Support Network (the coordinating organ of the European meteorological institutes) presented a report at the United Nations Climate Convention in Berlin, March–April 1995. The report concluded that the observed temperature changes in Europe and the North Atlantic from 1951 to 1990 are within the range of natural variation, and that anthropogenic climate change is expected to be detectable "in the course of the next century, but probably not before 2010, 2020, or 2030" (Schuurmans et al. 1995).

The Hadley Centre for Climate Prediction and Research (Bracknell, England) also presented a report at the Berlin conference. The Hadley global climate model, which takes the effect of aerosols into account, indicates a rise in mean temperature of 0.2°C per decade from 1990 to 2050 on the assumption that the total equivalent atmospheric CO_2 concentration of all greenhouse gases (CO_2, CH_4, N_2O, CFCs) increases at 1 percent per year from 1990 onward (Hadley 1995). No assumptions were made concerning the distribution of the incremental radiative forcing among the greenhouse gases, but if the forcing from atmospheric CO_2 increase in 1990–2050 is assumed to constitute 72 percent of the total forcing in the same period (as in the 1995 IPCC scenario), then the atmospheric CO_2 concentration would increase at 0.72 percent per year, and reach 545 ppmv in 2050. The Hadley scenario is thus comparable to WEC Case A.

7 "Long records show that, at least in Central and Northern Europe, the present warm period in Europe is at about the same level as measured 200 years ago" (Schuur-

mans et al. 1995). The temperature at Hohenpeissenberg, a 988-meter peak in Bavaria, has been monitored since 1781. The temperature rise since 1890 was preceded by a decline of equal magnitude, which started around 1800 (Laut 1995). The decline must have been preceded by a rise greater than that in the twentieth century, as temperatures in Europe in the 1690s are known to have been the lowest in the past thousand years (Lindgrén and Neumann 1981).

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