ENERGY DEMAND AND SUPPLY, 1900–2100

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SCIENTIFIC AND TECHNOLOGICAL PAPERS

ENERGY DEMAND AND SUPPLY, 1900-2100*

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ABSTRACT

One basic work of IIASA project on Environmentally Compatible Energy strategies (ECS) is a detailed assessment of specific technologies that might play a role in scoring well, with respect to the conflicting objectives of development and environmental protection. The result of this assessment is technology inventory, labelled CO2DB (Messner and Strubegger, 1991). CO2DB is a data base, implemented on Personal Computers, including technology descriptions, their environmental and economic characteristics as well as information on technology diffusion (temporal and geographical) and transfer. Currently, CO2DB contains information on more than 1400 technologies.

A recent synthesis of ECS work in the past years was the creation, in collaboration with the World Energy Council (WEC), of long-term global energy scenarios (WEC-IIASA, 1995). Among others, the IIASA-WEC scenarios aim at assessing how these technologies might be put into widespread use, to minimize the emission of greenhouse gases (GHGs) and to serve the development of all world regions. This paper describes selected results of the IIASA-WEC scenarios and summarizes the basis on which they are built. In this way, readers can form their own opinion on the results. We begin by analyzing past energy-demand and supply, together with its most important determinants. The main aspect of their scenarios is that (i) fear of exhaustion of resources seems to have been exaggerated in the wake of the oil price hike of the 1970's and (ii) each link of the causal chain between green-house gases emissions, climate change, and subsequent damage is not sufficiently understood to allow precise forecasting, and it seems wise for policy-makers to act on the principal of making mid-course corrections to their chosen energy strategies, on the basis of new knowledge and R & D for energy-efficient technologies

1. HISTORY OF ENERGY INTENSITY

The International Institute for applied Systems Analysis (IIASA) is an interdisciplinary, non-governmental research institution located in Laxenburg near Vienna, Austria. The Institute's research is focused on three central themes, (1) Global Environmental Change, (2) Global Economic and Technological Transitions, and (3) Systems Methods for the Analysis of Global Issues. One of IIASA's projects that cuts across themes (1) and (2) is the *Environmentally Compatible Energy* Strategies (ECS) Project, which focuses on the challenge of providing adequate energy services to a growing world-population while minimizing environmental impacts. The prime objective of ECS' work is a better understanding of the linkages between energy use, development and environmental impact, in particular global climate change.

For a systematic view of the energy-system, its environmental impact in the past and in the future, it is useful to disaggregate total energy demand into components. Following, e.g., Kaya (1991), total carbon emissions can be represented by the following identity:

$$CO_2 = cap * \frac{GDP}{cap} * \frac{TPE}{GDP} * \frac{CO_2}{TPE} \qquad (1)$$

where CO_2 = Carbon emissions
cap = Population
GDP = Gross Domestic Product
TPE = Total primary energy demand

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In this equation, total primary energy demand is conceptualized as the product of population, a measure of welfare (GDP per capita), and the primary energy-intensity of the economy. Emissions of carbon dioxide, the main energy-related greenhouse gas, can be thought of as the product of primary energy and its carbon intensity. Using this concept opens the door for using results of three scientific fields-demography, economics, and engineering- to explain and to project energy-demand and its aggregate environmental impact. We shall now look at the historical trends of each of the variables in turn.

Global Primary Energy Consumption: Total global primary energy-consumption, including all sources of commercial energy and fuelwood, has grown at an average annual rate of approximately 2% per year for more than one century (IPCC, 1996). This growth corresponds to a doubling of consumption every 35 years. Including fuel wood in measuring total primary-energy is important for the assessment of the development of energy-intensity of GDP. If non-commercial fuels are omitted, the average energy-intensity can show potentially misleading rises over time.

Population: Since the beginning of this century, global population has increased from 1.6 billion to more than 5 billion, corresponding to an average annual growth rate of 1.3% (See e.g. Grübler and Nakicenovic, 1994).

Economic Growth: Long-term economic growth is best observed in industrialized countries. According to Maddison (1989), the average per-capita GDP in 32 industrialized countries increased from US$(1980) 841 in 1900 to US$(1980) 3678 in 1987, that is , at an average annual rate of 1.7%. Population in these 32 countries grew at the same annual 1.3% as the global population, so that total GDP in these 32 countries grew at an average of 3% per year.

Decarbonization: Since 1860, the carbon-intensity of primary energy supply has decreased at an average annual rate of 0.3% (Nakicenovic et al., 1993). Taking this rate, together with long-term growth rates of primary energy consumption and GDP, we find that the carbon intensity of GDP has decreased at an average annual rate of 1.3%.

2. ENERGY INTENSITY OF GDP

From the numbers presented so far we can derive a long-term trend of energy-intensity reduction of GDP of 1% per year. This is the result of 3% economic growth and 2% growth of total primary energy demand. A more detailed picture of the development of energy-intensities is given in Figure 1.

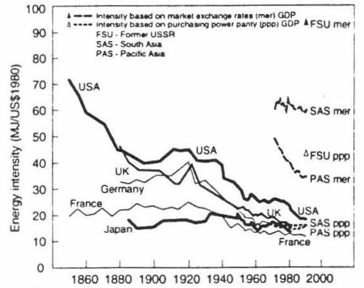

Figure 1: Primary energy (including wood) per constant GDP. Source IPCC (1996).

Figure 1 not only shows a large variety of energy-intensities of GDP in different countries and at different times, but it also makes the distinction between two ways of measuring GDP. The conventional way is to measure GDP in US dollars, converted at market exchange-rates (expressed by the index mer). Since the conversion at market exchange-rate ignores differences in purchasing-power between different economies, GDP in countries with high purchasing-power of the US dollar (or, equivalently, where prices are lower than in the US), seems lower than the same kind of product produced in the US. Since GDP is the denominator in the definition of energy-intensity, distorting the GDP to the low side results in misleadingly high values for energy-intensity. Correcting conventionally measured GDP for purchasing power (expressed by the index ppp), therefore, makes a significant difference for the resulting energy intensities, as shown in Figure 1, in the Former Soviet Union (FSU), South Asia (SAS), and Pacific Asia (PAS).

Taking all curves in Figure 1 together, the general picture is one of ever-decreasing energy-intensity, with significant differences between countries. Here, it is important to remember that we include non-commercial energy in our analysis. Other studies, e.g., Goldernberg et al. (1990), do not inculde non-commercial energy in their calculations of energy-intensity and, therefore, find peaks that are not visible on our graph.
Numerical examples of average annual decline-rate of energy-intensity, based on Figure 1 are given in Table 1.

Table 1: Average annual decline-rates of energy-intensity (%). Source IPCC (1996).

Country	1913-1988	1970-1988
United States	-0.93	-1.76
U.K	-1.32	-2.59
Germany	-1.31	-1.58
France	-0.93	-1.06
Japan	-1.30	-2.73

Typical and long-term decline rates are between 1 and 1.5% per year. In periods of higher energy price (e.g during the seventies and eighties of this century), we find higher rates.

As a further illustration of the difference between GDP measured at market exchange rates and the estimated purchasing power, we show extreme ratios between these two measurements in Figure 2.

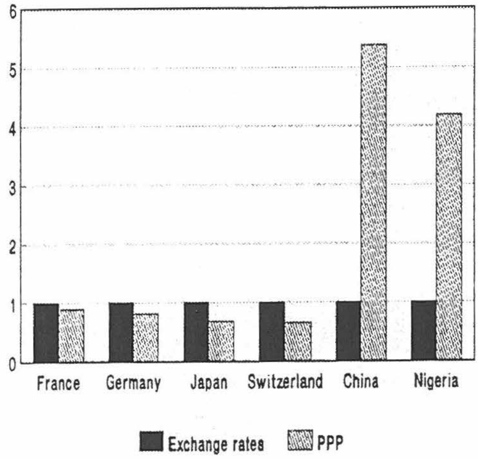

Figure 2: Exchange rates and purchasing power ratios. Source: UNDP (1993).

The data presented in Figure 2 suggest that countries with higher per-capita GDP have a lower purchasing power in US dollar equivalents, and it can be expected that the price-level in countries with presently high purchasing power will increase, reducing the big differences between purchasing power and GDP measured by conventional means, as shown in the figure.

The change of purchase power over time has not only an effect on energy-intensity calculations but also on economic growth rates. If the purchasing power in a country like China decreases from its present value of more than 5 times the US value, then GDP growth-rates decrease, as a consequence, if GDP is measured in purchasing-power equivalents rather than at market exchange rates. Since China is a big factor in any projections of future GDP and global energy-demand, these concepts play a crucial role in long-term global energy scenarios. Table 2 illustrates the divergence in GDP growth rates since 1971, using the market exchange rates and the purchasing power parity, for the Chinese economy.

Table 2: Average annual rates of growth for China (%)

Period	GPD at Market Prices	GDP at Purchasing Power Parity
1971-81	5.32	4.31
1981-91	8.73	6.48
1971-91	7.03	5.45

3. CONCEPTUALIZING THE RELATION BETWEEN ENERGY AND THE ECONOMY

Thus far, we have presented a conceptual factorization of total energy-demand without talking about causal relationships. The mere concept of energy-intensity suggests a tight relation between energy-demand and economic output. Indeed, GDP is one of the two determinants included in all descriptions of energy-economy interactions. The other factor is energy price. The simplest conceptual model, describing energy-demand, uses the price of energy and total economic output as the two independent explanatory variables. Two plausible but hypothetical assumptions lead to a functional form of this relationship. The first assumption is that the production of an additional unit of GDP requires the same energy-input as an average unit of GDP, that is, that GDP and energy-demand grow at the same speed. Second, assuming that energy -consumers operate with a fixed budget, a price increase of 1% is assumed to lead to a decrease of demand by 1%. These assumptions lead to the following formula

$$\frac{E_t}{E_o} = \frac{GDP_t}{GDP_o} / \frac{P_t}{P_o} \qquad (2)$$

The subscript t expresses time, 0 a reference time, relative to which changes for the three variables are measured. In other words, energy-consumption growth is a direct function of economic growth and is inversely related to price changes. This literally translates the mathematical formula into a verbal description.

The first refinement of this simple equation is to introduce elasticities into the rigid relationship of formula (2). Elasticities are introduced by exponents that, depending on their size, either dampen or magnify the reaction of energy-demand to changes of production or price. The original formula (2) then becomes

$$\frac{E_t}{E_o} = A\left(\frac{GDP_t}{GDP_o}\right)^{\alpha} * \left(\frac{P_t}{P_o}\right)^{\beta} \qquad (3)$$

Assuming income to be proportional to total production (i.e. assuming that macro-economic consumption is a constant share of total production), the exponent α is called income elasticity. For easier reading, the quotient of (2) was turned into a product in formula (3). As a consequence, β, the *price elasticity*, is normally *negative*. Since durable energy-consuming devices create a "lock-in" effect that makes it more expensive for consumers to respond quickly to price changes, a distinction is usually made between *short-term* and *long-term elasticities*. Numerical values are different in different situations, but -0.2 and -0.5 are indicative values for short-term and long-term elasticities, respectively. These express the fact that a 1% price increase leads to a demand reduction of 0.2% in the *short term* or to 0.5% in the *long term*. These values indicate that the first, "naive" assumption about a (negative) unitary elasticity is a far away from what is observed in reality.

To analyze the impact that energy-prices have had on energy demand in the past, we turn to Figure 3, showing the development of real energy and oil price in the US over more than 100 years.

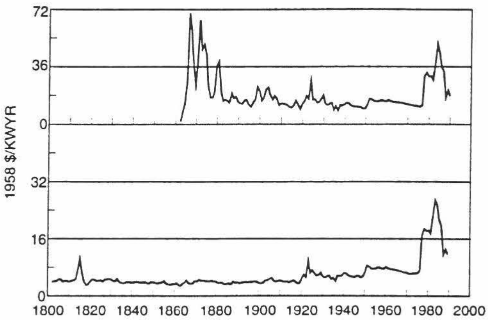

Figure 3: Real average energy (lower curve) and oil prices (upper curve) in the US since 1800. Source: Grubler (1990)

The overall picture of energy-price development in the US is one of a rather flat trend, with interspersed spikes. This picture is in distinct contrast to long-term trend of GDP development which, in most countries, show a persistent upward trend. In the light of formula (3), this means that influence of GDP growth on energy-consumption must be more significant than changes of energy prices. Assuming a *long-term* average zero growth of energy-price, in conjunction with the rough annual growth-rate of 3% for GDP and 2% of primary energy as above, we thus get an income elasticity of two-thirds. As in the case of price elasticities, this means a dampened effect of GDP changes on changes in energy-demand. Instead of the concept presented, that is, where α influences demand via GDP, other ways of decreasing energy-intensity can be formulated. Some modelers, for instance, prefer to include the same phenomenon as time-dependent and vary the coefficient A of equation (3) instead.

Independent of the model used, the reduction of overall energy-intensity is the consequence of several causes. Among them are *technological progress*, which tends to make energy-conversion processes more efficient; *economic structural change*, which (at least in later stages of economic development) usually goes into the direction of greater shares of less energy-intensive sectors, such as the service sector, and *fuel switching*, which is normally accompanied by a reduction of energy-intensity.

4. PROSPECTS FOR FUTURE ENERGY-INTENSITY REDUCTION

To asses the prospects for future energy-intensity reductions, it is useful to conceptualize the energy-system, distinguishing various energy-forms. Figure 4 illustrates schematiclly the different levels of energy-conversion between primary energy sources and energy services.

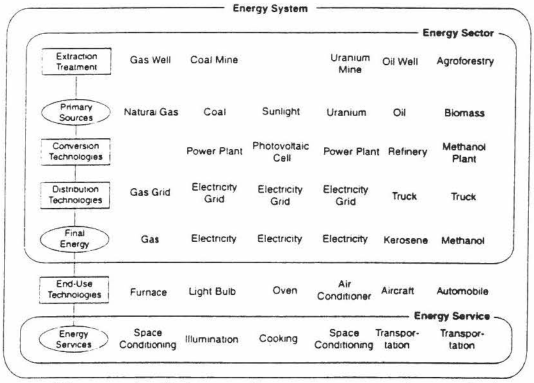

Figure 4: Schematic representation of the energy system. Source: IPCC (1996)

The first important thing to note is that there is a long way to go between a primary energy-source and the purpose of energy end-use. In fact, there is a huge qualitative difference between, e.g. a barrel of crude oil and a person transported over a certain distance. As it turns out, also the quantitative difference is important in long-term studies of the energy-system and the question arises why, so often, primary (and not final) energy is used as an indicator of energy intensity. The answer is simply that primary energy is so much easier to measure, and that the difference in results is often negligible. Ideally, however, the relationship between final (instead of primal) energy and economic output should give a more accurate picture, in particular of energy-systems that include a significant share of synthetic fuels (such as methanol or hydrogen) or solar energy.

Looking at the energy-quantities flowing through the system, we find a total energy-conversion efficiency between primal and useful of just under 30%. (see Figure 5)

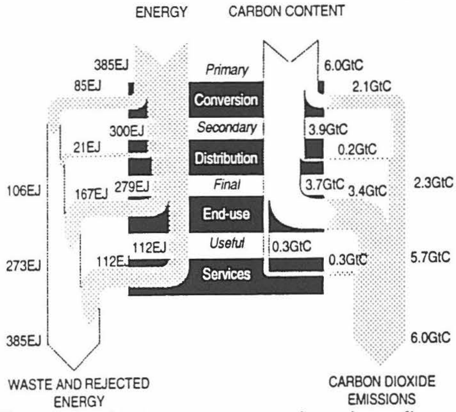

Figure 5: Major energy and carbon flows through the global energy system in 1990. Carbon flows do not include biomass. Source IPPC (1996).

In order to judge whether these 30% are much or little, it is important to note that not all energy leaving the system, before performing the ultimate energy-service, is wasted, in the sense of being used without a good purpose. For instance, the efficiency of thermal electricity generation is limited by *Carnot's Law* which describes a theoretical upper limit of the thermal efficiency of power-generation. This efficiency is a function of the difference between the ambient and the process temperatures. Using a realistic but simple illustrative example of 300K (27°C) for the ambient and 1000K (727°C) for the process temperature, the maximum efficiency according to Carnot is 70% (1-300/1000). At the same time, some of the traditional uses of final energy can be replaced by heat transfer, for example a heat pump. Traditional energy-conversion efficiency would be a misleading indicator in such cases: the theoretical minimum energy required for providing a temperature of 30 °C to a building where the outdoor temperature is 4°C is one twelfth of the heat-energy delivered to the indoors (IPCC 1996).

These considerations of efficiency limits are useful for the calculation of theoretical limits to energy-efficiency of different energy-conversion. In practice, the concept of Best Available Technologies (BATs) is a useful tool to estimate practical energy-saving potentials. Nakicenovic et al (1993) estimate that 40% of global energy use in 1990 would have been saved by using BATs in every instance of energy conversion. This is still a theoretical consideration, but it tells us that the hypothetical instantaneous effect of introducing BATs is equivalent to more than 50 years of continuation of the long-term trend of average energy-intensity improvement. (An annual reduction of energy-intensity of 1% leads to a reduction of the base-year energy-intensity to 60% in 51 years).

The BAT concept ignores costs, however, and an estimate of near-term realistic energy-savings potentials must look at the cost of investing in energy-efficiency improvement. Estimates summarized in Nakicenovic et al (1993) suggest an economic potential of economic energy-savings in the Industrial and Residential/Commercial sectors of 13 and 14% repectively. These figures must to taken as indicative only, because they rest on a number of assumptions that are debatable. Also, techno-economic potential cannot readily be translated into overall energy-intensity reductions, as the discussion in the following section is intended to show.

A more detailed example of an assessment of sectoral energy-savings potentials and their costs is shown in Figure 6. The figure shows the electricity-savings potential of the US buildings sector versus conservation costs for a range of discount rates.

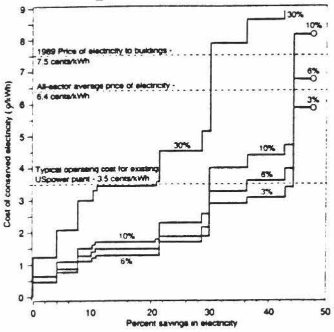

Figure 6: Electricity saving potential of the US buildings-sector versus conservation costs for a range of (real) discount rates between 3% and 30%. Source: NAS (1991)

The figure shows that the savings-potential depends crucialy on the discount-rate used in the calculation. The highest rate used for the illustration, 30% may seem very high. This may be so when compared with bank rates. In this example, discount-rates play the role of a technical parameter that is varied to explain "user-behaviour". This point is discussed in more detail in the following section.

5. METHODOLOGICAL CONSIDERATIONS

Without explicitly emhasizing it, we have shifted the discussion from energy-demand, as a function of economic output and price, to energy required to perform a given task. This has some methodological implications when it comes to forecasting energy-demand or to calculating costs of energy-saving and pollutant-emission reduction.

First, we note that increasing the energy-efficiency of a given task, in effect, reduces the energy-costs involved and therefore can be expected to have the same effect as an energy price reduction. According to formula (3) above, this can lead to an increase of energy-demand. This has been called "take-back" effect. An example of this effect in action is given in Figure 7, showing that a more than 30% reduction of specific gasoline-consumption by US passenger cars between 1970 and 1989 did not achieve a reduction of total gasoline consumption. The offsetting factors preventing it were an increase of the total distances driven and a decrease of the average number of passengers per ride.

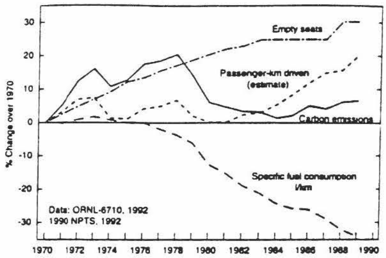

Figure 7: Carbon emissions from US passenger cars. Source: Grubler, IIASA, (1993), unpublished.

Another caveat is that for many consumers, energy-efficiency is only one of several often conficiting criteria for purchasing decisions. Passenger cars are an example that should make this point fairly obvious.

From this discussion, it follows that the costs of energy-saving and pollutant-emission reduction can be estimated in two principally different ways. One is to calculate the cost of technical improvement ("Bottom-Up") and the other method ("Top-Down") is to regard energy-prices as a controlled variable (e.g. by assuming price-regulation by taxes and subsidies), to estimate the functional relationship between price and demand, and to calculate aggregate output (GDP) losses as a function of an energy or carbon tax.

It is clear that in the latter case of Top-Down analysis, reducing any reference energy-demand incurs reduction costs. This view, normally attributed to economists, is illustrated in Figure 8, compiled by Nordhaus (1991). The figure clearly expresses the economists' paradigm that "*there is no free lunch*"; that is, any reduction of CO_2 emissions (or, equivalently, energy intensity) is accompanied by energy-price increases.

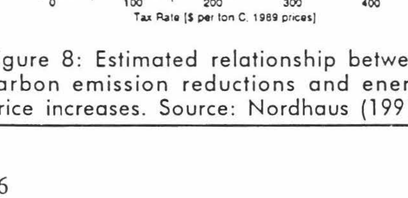

Figure 8: Estimated relationship between carbon emission reductions and energy price increases. Source: Nordhaus (1991).

Nordhaus' curve is in clear contrast to the possibility of saving energy, emissions, and costs at the same time, as suggested by Bottom-Up studies such as the one summarized in Figure 6. Even when considering that the two methods answer different questions, confusion may arise from the discrepancies between these two kinds of results, and thus not permit rational policy-making. It, therefore, seems worth while to probe these differences further.

Observing the scientific and public discussions held on the subject, it may seem that these discrepancies may never be rconciled, but much of the differences of opinion about the size of potential savings are related to the question: *Why are economically profitable energy savings potentials not realized by the consumers ?* Or, in the economists' jargon: Why are free lunches not consumed ? We think that it is obvious that at least some of the "free lunches" are not consumed due to the lack of appropriate information. It would be easy to lump these two reasons together under the label, *transaction costs*, but for policy-making, aiming at energy-intensity reduction, these two reasons would seem to require different strategic approaches.

From the descriptive point of view, it seems clear that market discount-rates are an inadequate tool for describing consumer-behavior and that their indiscriminate use in analyses, therefore, underestimates costs and overestimates potential savings. This conclusion is based on Hausman (1979), who calculated implicit discount-rates by observing consumer-decisions trading off initial investments against later savings, when purchasing air conditioners. His results are given in Table 3.

Table 3: Implied discount rates in purchases of air conditioners in US households. Source: Hausman (1979).

Income Class US $ (1979) per year	Implied Annual Discount Rate (%)
6,000	*89.0*
10,000	*39.0*
15,000	*27.0*
25,000	*17.0*
35,000	*8.9*
50,000	*5.1*

They show that consumer behavior, particularly in low-income classes, is inconsistent with the assumption of personal discount rate that are of a similar size as bank rates. But not only private consumers can act as if their individual discount rate is very high. According to Ross and Steinmeyer (1990), a typical criterion for US companies to decide whether they should invest into energy-saving measures or not is an estimated pay-back time of 2 to 4 years. This criterion corresponds to discount rates of the order between 25 and 50%. Regrettably, such high discount rates do not answer our question from above, whether real costs are overlooked in some calculations of energy savings potentials or whether they just reflect the lack of information. In either case, however, standard-setting is a policy tool that addresses the problem of promoting energy-efficient equipment at low or even negative extra costs.

These points explain some of the differences between the two types of modelling approaches. They do not account for all differences, but they characterize a main problem area. Being aware of these potential problems should identify the places at which judgment-both on the side of analysts describing potentials and the recipients of the results-enters the scene of assessing concrete saving-potentials. If the purpose of assessing costs of energy saving is demand forecasting, it is important to realize that bottom-up savings potentials are usually static, that is they describe a theoretical situation at a given point in time. The observations presented above suggest that a striaghtforward cost-calculation of supplying energy for a given task may miss some of the factors determining actual future energy demand. We, therefore, think that calculations of energy-savings costs that involve the specfication of technical saving-potentials ought to explicitly address the question of demand-forecasting, by including a discussion of time-paths that might lead to its realization.

6. ENERGY RESERVES AND RESOURCES

The history of estimating natural resources, in general, and energy resources, in particular, is characterized by a recurring concern about finiteness. In those cases where this concern was formulated as a projected date of exhaustion of a particular energy-reserve, the record of past errors is impressive. (See, for instance, Wildavsky and Tenebaum 1981). One reason for expecting impending exhaustion of primary energy is the lack of appreciation for the difference between resources and reserves. According to McKelvey (1972), reserves are that part of resources, that has been assured to exist in known places, and that can be economically recovered under prevailing prices. Gradual relaxation of the first criterion leads to the subeconomic resource-categories, and relaxation of the second criterion defines hypothetical and speculative categories. From this definition, it is clear that reserves are the result of a dynamic process and that any price-increases or new geological information transfers a part of resources into reserves.

An often-used and very suggestive indicator

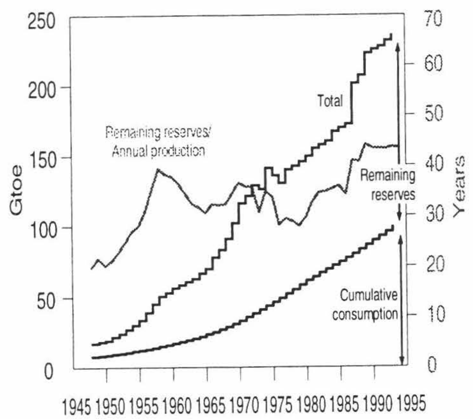

Figure 9: Development of oil reserves, cumulative consumption and reserves-to-production ratio. Source: WEC-IIASA (1995)

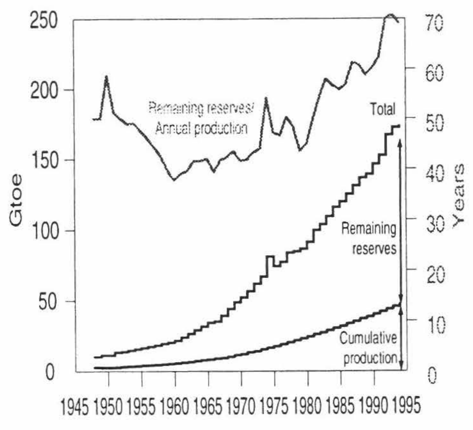

Figure 10: Development of natural-gas reserves, cumulative consumption and reserves-to-production ratio. Source-WEC-IIASA (1995).

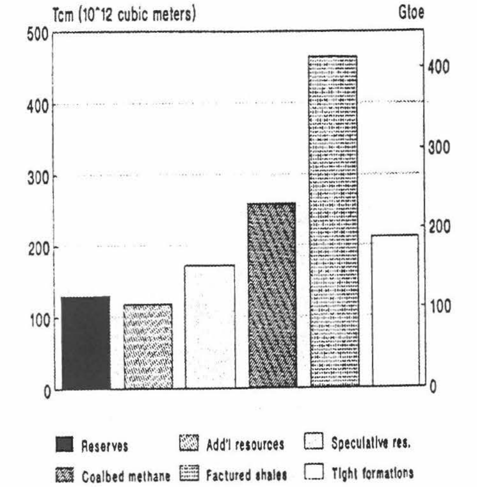

Figure 11:Categories of global natural-gas occurrences. Source: ISGS (1993).

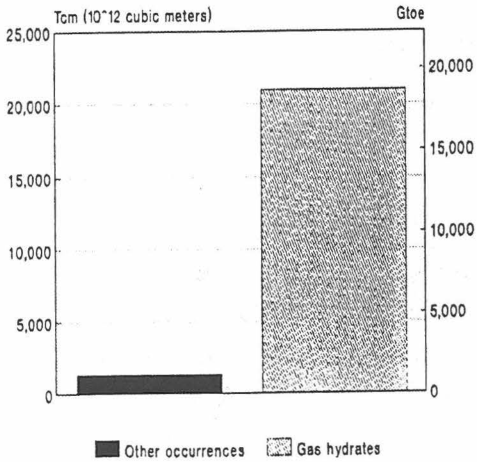

Figure 12: Estimated global occrrences of natural-gas hydrates. Source: USGS (1993).

of the size of energy-reserves is *reserves-to-production ratio*. This hypothetical number is the result of dividing, for a given year, reserves of primary energy-carrier by its annual production. The reserves-to-production ratio is therefore give in years and expresses how long it would take to exhaust a given reserve under the assumption of constant production. As we have seen, this number is hypothetical in two respects, that is, neither production not reserves are constant over time.

A practical aspect of the quantification of reserves is that the collection of primary information on reserves and resources is costly, and that the interest, on the side of producers of such information, in preciseness of the estimates is limited. As far as reserves are concerned, producers are mainly interested in the near to medium-term and, as soon as production during a producer's planning-horizon is assured, further information is of little value.

Let us now look at the recent development of two particularly important resources, oil and natural gas. Figures, 9 and 10 show cumulative consumption, remaining reserves and the reserve-to-production ratios for these two resources during the past few decades. For both resources, remaining reserves have multiplied in this time period, and the reserves-to-production ratios have increased on the average. In particular, since the early 1970s, the time of the first oil-price increase, reserves of both oil and gas have been increasing significantly.

Looking more closely into the resource part, we show estimates of some resource-categories of natural gas in Figures 11 and 12. The figures are separated to show natural-gas hydrates (also known as "clathrates") resident in polar regions and in off-shore sediment of outer continental and insular margins (Kvenvolden, 1993) in huge quantities. Together, Figures 11 and 12 show that natural-gas reserves are less than 10% of gas resources, excluding natural-gas hydrates, and that hydrates are estimated to exceed the sum of all other categories by a factor of approximately 15.

Estimates of all fossil resources and of uranium are summarized in Table 4. The table shows that oil-resources are of approximately the same size as gas resources, if natural-gas hydrates are not include in the latter. Coal resources are more than 60% of the total fossil-resource base, as defined in table 4, and total geological occurrences of fossil primary-energy are dominated by gas hydrates.

The size of the natural uranium resources cannot be readily expressed in energy-units, because the amount of secondary-energy generated with uranium depends on the kind of technology used, for e.g., power generation. Table 4 uses two illustrative figures for each category of natural uranium resources. The first and lower number assumes the use of natural uranium for power-generation exclusively in conventional burner-reactors such as the Light Water Reactor. The second number assumes its use in advanced reactors such as Fast Breeder Reactors (FBRs) only. Such reactors can increase the power-output by a factor of approximately 60 in comparison to conventional reactors. Together, these two numbers give a wide but illustrative range of the natural-uranium resource base. The estimates in Table 4 were the basis of the resource-availability figures put into the IIASA-WEC scenarios which are presented in the following section.

Renewable sources are not included in Table 4 because they are unlimited for practical purposes. Only the rate of their utilization and market-penetration is assumed to be limited. These limits are not explicitly reported here. They can be found in WEC-IIASA (1995), but they can also be work was done jointly with the World Energy Council (WEC) and was presented at the

Table 4: Global fossil and nuclear energy reserves, resources, and occurrences, in Gtoc. Source: WEC-IIASA (1995)

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

- negligible amounts; blanks, data not available
[a] Resources to be discovered or developed to reserves
[b] Resource base is the sum of reserves and resources
[c] Includes natural gas liquids
[d] All totals have been rouded
[e] Fast breeder reactors

7. LONG-TERM SCENARIOS OF THE DEVELOPMENT OF THE GLOBAL ENERGY SYSTEM

The determinants of the long-term development of the global energy system can be grouped into three areas: resources, technological progress, and demand. We have discussed these categories here: resources and demands, explicitly, and technology, implicity, in the section on potentials for energy-intensity reduction. A synthesis of the research conducted by IIASA's ECS Project in the past years in these three areas is the formulation of global long-term energy and emission scenarios. This approximately inferred from the secnario-results reported in the following section.

16th WEC Congress held in Tokyo in 1995. The input assumptions determining the scenarios, also called *scenario variables*, are varied across ranges of plausible values. In one case, this principle was not followed, and a normative scenario resulted, in which the consequences of an unrealistically high degree of global cooperation aiming at achieving ambitious environmental goals is analyzed. The purpose of this scenario was to give a quantitative illustration of the efforts required to stabilize global atmospheric concentrations below 450 ppmv, a value well within the often-quoted doubling of pre-industrial levels. In the remainder of this section, some key results of the IIASA-WEC results are presented. (For a more detailed description, see WEC-IIASA (1995)).

Table 5: 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
Technoclogy cots			
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 emission, GtC			
2050	9-15	10	5
2100	7-22	14	2
Environmental taxes	No	No	Yes

The geographical basis of the IIASA-WEC scenarios is a disaggregation of the globe into 11 world-regions. Although most scenario-results are described in 11-regional detail, the WEC-IIASA report presents mainly global totals and aggregation of the 11 regions into three "macro" world regions: OECD, Reforming Economies (of Eastern Europe and the former Soviet Union), and Developing Countries. Here, we will restrict ourselves to looking at global aggregates. The IIASA-WEC scenarios are divided into three sets. *High Growth (A), Middle Course (B), and Ecologically Driven (C)*. The main characteristics of these three sets are summarized in Table 5.

Case A represents a future of ambitiously high economic growth-rates, a favourable geopolitical development, including largely unimpeded international trade. High economic growth (at a global annual average of 2.4% between 1990 and 2100)is assumed to facilitate a comparatively rapid turnover of capital stock, thus allowing technological progress and economic structural change (leading to a relative increase of less energy-intensive service-sectors world wide) to permit continuing reductions of aggregate energy-intensity at an average annual rate of 1% between 1990 and 2100.

Case B incorporates more modest economic development (an annual average of 2.1% per year) and somewhat less optimistic assumptions about energy-intensity reduction (0.8% per year averaged), but like Case A, it assumes the expansion of international trade as the consequence of the demise of trade-barriers.

Case C, the normative of the three cases assumes that global environmental protection will drive policy-making world-wide. Unprecedented international cooperation thus leads to a high degree of environmental protection and international equity. Unrealistic as Case C may seem, it quantifies a specific set of efforts that would lead to a reduction of global carbon emissions by two-thirds of their 1990 value by the year 2100. (2 instead of 6 billion tons of carbon per year).

To limit the variability between the cases and to enhance their comparability, all three cases are based on identical assumptions about global population growth. According to these assumptions, the global population saturates below 12 billions, passing 10 billion just before the middle of the next century. Another common feature of the cases is that they assume a reduction of the income-gap between industrialized and presently developing world-regions. The mechanism with which this income-discrepancy is reduced is included in the guiding principle of projecting economic growth more than 100 years into the future. In the IIASA-WEC scenarios, it was assumed that GDP growth-rates are a decreasing function of per-capita GDP, that is, world regional GDP growth decreases with increasing wealth in that world-region. This dependency is summarized in Figure 13.

Total global primary energy-consumption for all three cases in shown in Figure 14. As an insert, the figure also shows the world population. Both graphs show the historical development since 1850 and the projections through the year 2100.

Average annual growth over the whole time-horizon of primary-consumptions is slower than the long-term historical trend in all three cases, that is, 1.5% in *Case A*, 1.2% in *Case B*, and 0.8% in *Case C*. Much of this reduction of growth-rates occurs in the second half of the next century.

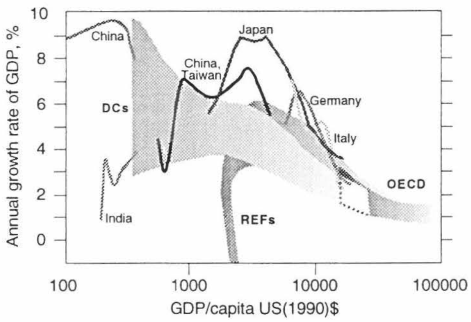

Figure 13: Economic growth-rates in relation to per capita GDP. Historical data for selected countries and ranges for the three IIASA-WEC cases in three macro world regions. Source: WEC-IIASA (1995).

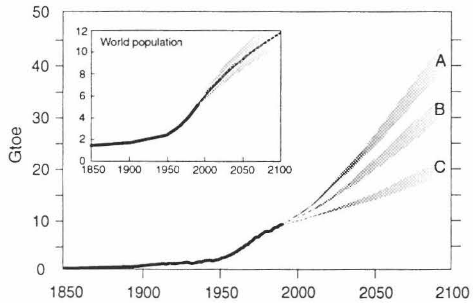

Figure 14: Global primary energy use, 1850 to present, and the three cases to 2100, in Gtoe, Insert: Global population, historical and projected. Source:WEC-IIASA (1995).

In terms of primary energy-supply structure, *Scenario A1* might be the most realistic of the three scanarios of Case A. In contrast to A2 (in which coal is the dominant primary-energy carrier) and *A3* (relying more on nuclear and renewable energy than the other scenarios of all cases), *A1* assumes technological progress to favor developing the vast potential of conventional and unconventional oil and gas-occurrences. The main result presented in this picture is that, even without including gas hydrates, a scenario can be defined that relies to 40% on oil and gas as primary-energy carriers for more than 100 years to come.

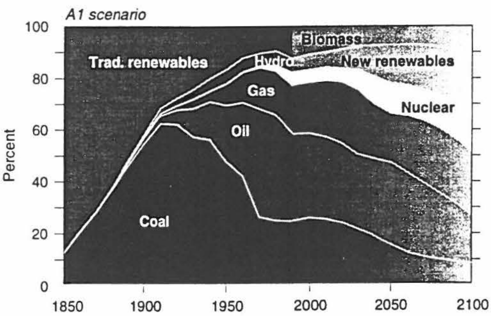

Figure 15: Evolution of primary energy shares 1850-2100, *scenario A1*. Source: WEC-IIASA (1995).

Case B consists of a single scenario. Consistent with its more cautious assumptions about economic growth, the additions to oil and gas reserves are assumed to develop at more modest rates than in *A1*, and coal is gaining an increasing share of all fossil fuels. Figure 16 shows the evolution of primay energy shares in *Case B*.

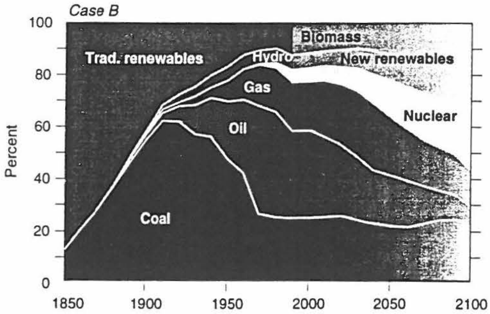

Figure 16: Evolution of primary energy shares 1850-2100. *Scenario B.*
Source: WEC-IIASA (1995)

Case C includes two scenarios, *C1* and *C2;* these two scenarios differ with regard to nuclear energy. C1 reflects the more conventional "green" perspective of nuclear energy to be undesirable and, therefore, includes a phase-out of nuclear energy by the year 2100. In contrast, C2 assumes that nuclear energy can make an environmentally and socially accepted contribution to global primary-energy supply, e.g., by a newly developed decentralized and inherently safe conversion-technology. Here, we show the evolution of primary-energy shares in *Scenario C1* in Figure 17.

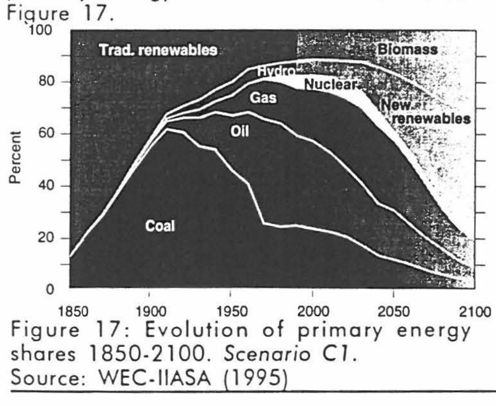

Figure 17: Evolution of primary energy shares 1850-2100. *Scenario C1.*
Source: WEC-IIASA (1995)

Scenario C2 has a similar structure of primary-energy shares as *C1*, the main difference being a share of nuclear energy that slowly grows to 20% by the year 2100. Note that absolute total primary-energy consumption in *Case C* is much lower (approximately 50% in the year 2100) than in *Case A* and that, therefore, the shares in Figure 17 correspond to correspondingly lower absolute numbers of resource-consumption.

Fossil primary energy-resource consumption in all IIASA-WEC scenarios is summarized in Figure 18. Expressed as shares of the respective resource-base (reserves plus estimated resources of Table 4), neither oil nor gas consumption exeeds 80% until the year 2100 in any of the scenarios. Note that natural-gas hydrates were not included into the resource-base of any of the six scenarios. By the end of the next century, five scenarios, that is all except the coal-intensive *Scenario A2*,use less coal than the presently estimated reserves.

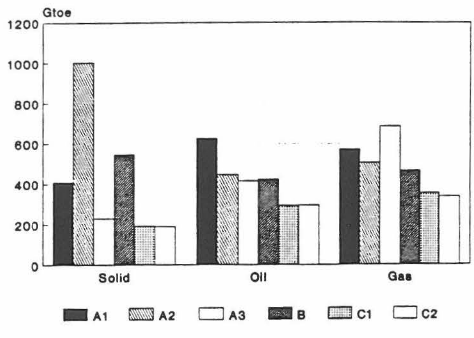

Figure 18: Cumulative extraction of fossil resources in six IIASA-WES scenarios.
Source: WEC-IIASA (1995)

Summarizing the environmental impact of the 6 IIASA-WEC scenarios, we show in Figure 19, th global atomospheric CO_2 concentrations and temperature change between 1950 and 2100. Both of these variables can be projected only with substantial uncertainties, even when the energy-related CO_2 emissons are known exactly. For example, uncertainties surrounding the increase in temperature expected for *Scenario B*, the central indicator, with regard to these aggregated indicators of environmental impact, cover the middle values of all six scenarios; the emissions lead to doubling of pre-industrial CO_2 concentrations by the year 2100 and an estimated global temperature change of 2°C. The highest environmental impact is in the coal-intensive *Scenario A2*, as could be expected. The highest-growth *Scenario A3*, which relies heavily on nuclear and biomass, has significantly lower carbon-emissions than the middle *Scenario B*. By design, global atmospheric CO_2 concentrations in *Case C* peak below 450 ppmv. Remaining below this limit should keep the global average temperature from rising by more than 1.5 °C.

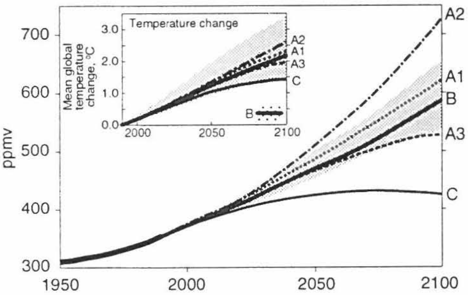

Figure 19: Global atmospheric CO_2 concentration (ppmv), 1950-2100, and global mean temperture change (°C), 1990-2100. The model uncertainties are indicated for *Case B* only. Source WEC-IIASA (1995).

8. CONCLUSION

In this paper we have presented the historical development of the main determinants of energy demand, a view of the present situation of golbal energy-resources and global scenairos of economic development, energy supply, and its environmental impact over more than a century into the future. The main aspect of the scenarios is that the fear of their exhaustion seems to have been generally exaggerated in the wake of the oil price hikes of the 1970s. Today, the development of further energy-sources appears to be less contained by their physical occurrence than by the carrying capacity of the global environment. The question whether this is good news or bad news is fraught with considerable uncertainty. Taking global climates as example, each link of the causal chain between greenhouse-gases emissions, climate change, and subsequent damages is still not understood in a way that permits precise forecasts.

For policy making, it would seem wise to act on a precautionary principle that allows mid-course correction of a chosen energy-strategy, should new scientific knowledge suggest that damages due to energy-conversion are expected to be significantly different from what they were assumed to be. Reasonable as this principle may sound, there is much disagreement around the world as to exactly what policies would be the result of its proper application. One class of policies that reflect the precautionary principle is the "no-regrets" policies. This class comprises those policies that pay off in any case, that is, they are economically attractive, even without including the environmental damges as externalities into the calculation. Whatever these may be in given situation, it seems clear that research and development of more energy-efficient technolgoies will have to play a major role in the pursuit of such policies.

General considerations quoted in this paper indicate that the theoretical potential of technological progress is still very high. Efforts to tap it promise to continue the historical trend of energy-intensity reduction for many decades to come.

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