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A CRITICAL APPRAISAL OF THE ENERGY SCENARIOS? -- A REBUTTAL

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A Critical Appraisal of the IIASA Energy Scenarios?

- A Rebuttal -

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The briefest form of this rebuttal is contained in the following three observations:

There is nothing easier than a solved problem [1].

The misunderstanding of the meaning of energy modeling is colossal.

At the heart of the issue is the old controversy "soft versus hard energy paths".

Before we elaborate on these observations it is appropriate to briefly describe the overall structure of the IIASA energy study, "Energy in a Finite World" [2], as this provides the proper factual basis for understanding the study's objectives, methods and findings. We regard this as essential since Keepin's critique admittedly concentrates only on one part of the study, namely the quantitative analysis and in doing so is a fundamental shortcoming of his critique.

The IIASA study consisted of a number of strata. It began necessarily with the goal of defining the nature of the energy problem, the proper temporal and spatial framework in which it should be viewed, and other leading factors. This included a scenariette of scenariettes: Figure 1-5 in [2][#] illustrates the expected evolution of the world population over the period 1975-2030. Currently the world population is some 4 billion and the average global per capita energy

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Where appropriate we use throughout this rebuttal the notation of the IIASA energy study Energy in a Finite World [2].

consumption is 2 kWyr/yr, resulting in a total energy consumption of some 8 TWyr/yr. If as anticipated the population in 2030 is some 8 billion people, total consumption would be 16 TWyr/yr if the average per capita consumption remains constant. If the per capita consumption rises to 3 respectively 5 kWyr/yr, the total consumption would be 24 respectively 40 TWyr/yr. These are straightforward calculations that do not even require the "back of an envelope". The conclusions are indeed sweeping. In order to properly assess their implications and thereby the degree of plausibility, one has to disaggregate by going into detail.

The first stratum of the IIASA study addressed the question of resources, fossil as well as nuclear, solar and renewables. The method adopted was to stretch considerations to the limit in determining the mere existence of such resources, without considering such constraints as prices or existing technologies. The identified upper limits were at times surprising and in all instances educational. For example, in the case of soft solar energy--that is local and decentralized solar energy, the maximum supply potential globally is 1-2 TWyr/yr of energy. For nuclear energy the situation with respect to uranium resources could be viewed in the same finite manner as, say, for oil resources except when the principal of breeding is engaged which changes the picture radically.

At the second stratum the analysis focused on the constraints, primarily those of a global nature. Time was found to be a formidable constraint. As history has shown the transition from one technology to another as well as major infrastructural changes require time, which on a global scale could be as much as 100 years. The study also looked into how the requirements for water, energy, land, material, and man-power associated with energy installations could constrain the build-up and maintenance of such facilities. Large-scale solar power facilities, for instance, require, say, 50 kg per square meter of steel and concrete, which is a hard undertaking. The constraints posed by the climate system were studied in greater detail. The disposal of waste heat appears to be a non-problem globally, whereas the carbon dioxide problem poses probably a serious threat to the global climate system over the long term. Among the other constraints considered were the issues of standard setting and risk management. Here it is important to reflect the nature of IIASA: It is an international institute where East, West, North and South come together to deal impartially and scientifically with civilization problems irrespective of political and to a large extent social differences. Accordingly the intent is to deal with problems mostly on a factual basis and not so much with questions of perceptions of a given society.

It is only at the third stratum that the IIASA study undertook the task of balancing energy supply and demand. This involved the method of quantitative scenario writing by means of mathematical models. This was done for the world regions* that comprise the globe: "Energy in a Finite World". Here the objective was clearly to understand to the degree possible the interaction of the energy paths in one region with the energy paths of all of the regions. The objective was not to conduct a detailed analysis for, say, the OECD countries in harmony with the availability of many statistical data there and to ignore the energy situation in other world regions such as Africa and Southeast Asia. Thus it was necessary to opt for a method that by its very nature enabled one to grasp the situation in the OECD countries as well as, say in Africa, Southeast Asia, and the planned economies of the Soviet Union and Eastern Europe, and to view these from a globally consistent perspective. IIASA was particularly suited

* Region I (North America), Region II (Eastern Europe and Soviet Union), Region III (Western Europe, Japan, Australia, New Zealand, Israel, South Africa), Region IV (Latin America), Region V (Africa and South-East Asia, Region VI (Middle East and North Africa) and Region VII (China and other Asian centrally planned economies).

for this endeavor; more will be said about this modeling when we deal with the above mentioned observations.

What is important here is the fact that after a further stratum, where we gained certain perspectives from this balancing of supply and demand (e.g. on reconsiderations of technologies, on energy densities, land-use and settlement patterns, as well as on the hard/soft controversy), it is in Part VI of [2], that the IIASA study then undertook the essential and complex task of synthesis. This involved the findings of both the quantitative and the qualitative analyses that comprised the IIASA study. The assessments and implications of the study are reported in Part VI of "Energy in a Finite World" and cover the major elements of the energy problem: It is therefore regrettable that Keepin has elected to view the IIASA study only through the lens of the IIASA scenarios and thus to neglect the rest of the study in which the scenarios are embedded.

Let us now elaborate on our observation: "There is nothing easier than a solved problem".

One should recall the situation of the early seventies after the first oil price shock. To most experts and observers the energy problem appeared to be opaque. Generally speaking, only a limited number of aspects had come under scrutiny such as the oil market of the OECD countries or the electricity market in the FRG. Questions as to the nature of the energy problem as a whole and to what was at stake remained open. In the US for example, this period witnessed "Project Independence" [3] and its related analysis which made extensive use of large energy models. There was also the lengthy and tedious study known as the CONAES Report of the United States National Academy of Sciences [4]. As to the problems in, say, Asia or Latin America there was the input/output study "The Future of the World Economy" [5] conducted under the leadership of W. Leontief. This was meant to address mostly the problems of the developing countries, and to take into account the political goals of the "Group of 77" as expressed at several United Nations Conferences [e.g. 6]. During this period growth rates of the world economy as high as 5 percent per year were under consideration. The fact that such figures are simply not discussed today reflects the major changes in the conditions and perceptions that have occurred since the early and mid-seventies, when the IIASA energy study was conceived. Clearly, this study and others have contributed to a deeper understanding of the energy problem and in particular of its global aspects. We have gained knowledge and insights and to that extent the problem has been resolved.

A major component of these analyses was energy modeling. But the misunderstanding of the purpose of such modeling is often colossal. This appears to be the case particularly for Keepin.

Briefly, there are three ways of using mathematical models:

(1) Mathematical models can be used for prediction and forecasting. The principal example of this is in the field of physics. Once a law of nature is known, it is possible to predict the state of affairs as described by this law at time t1 when a previous state at time t0 is known. This kind of modeling has formed the consciousness of man since the days of enlightening, and many scientific disciplines besides physics have tried to follow similar lines.

(2) Mathematical models can be also used to describe complex and short-range trends even when the laws of nature or its equivalent are not known. A case in point is econometrics. By evaluating intelligently time series of past data, one can forecast within limits certain economic trends. While inherent shortcomings are admitted, it is by and large possible to apply such econometric modeling over a period of a few years. The goal here is

is to grasp the features of the *one* future that is to come.

(3) Mathematical models can also be used to describe in a consistent way scenarios of evolution and this means not the one future to come but rather several conceivable futures. The models are then used not for forecasting but for the maintenance of consistency and thereby for consistent disaggregation. As observed earlier, when dealing with such complex problems as the energy problem, it is generally not enough to make single sweeping and simple observations. Disaggregation then acts as a tool for understanding and determining the degree of plausibility. In this sense, the mathematical models serve as a brush for painting an overall picture whose observed pattern enhances ones understanding of what is plausible and what is not. It is for this reason that we consider such modeling a craft and not a science or an art.

Keepin's misunderstanding is therefore colossal as he seems to reach out for a mixture of modeling of the first and the second type, while in the IIASA study the modeling was meant to be of the third type.

Keepin's perception of the linear programming (LP) model MESSAGE [7] demonstrates this error even further. MESSAGE was used primarily to organize and process a large set of input data consistently for many cases and for the various world regions of the IIASA study. This was done while fully recognizing, among others, the following two features of LP models in general:

- The solutions are flip-flop in nature: the slightest advantage of one path over another makes the solution flip in spite of the fact that reality is in most cases not that way.
- Solutions become obvious--if not trivial--once they have been identified. Indeed, the solutions of an LP problem lie on the edges of linear manifolds of the active constraints. Once they have been identified, it is trivial to

follow them. But first they must be identified. It is therefore besides the point to speak of analytical emptiness.

Keepin has reinvented both known features. Indeed: *There is nothing easier than a solved problem.* But the educational benefits that went along with this problem solving process and the richness of the information gained from the disaggregation are lost when a scenario is replaced by a "scenariette". Producing a "scenariette" was simply not the point. Had this been the intent we would have ended with the scenariette of scenariettes described at the beginning of the article. Specifically, an important finding of the study is that the feasibility window is a narrow one; it is highly determined by constraints. When looking not at an infinite world as often perceived by single large nations, but at a finite world which reflects the interdependencies of all nations, there are indeed only narrow feasibility windows for dealing with the energy problem over the next fifty years. This communicates a kind of emergency quite in contrast to the relaxed attitudes that are characteristic of much of today's thinking.

Indeed, the information gained through analyses enriched the picture. That is particularly true for the evaluation of shadow prices and elasticities as given in Chapter 15 of Energy in a Finite World [2] (see in particular Tables 15-1, 15-5, 15-6, 15-7, 15-9, 15-11). Contrary to their function in econometric modeling, these prices and elasticities are outputs not inputs and can be used to monitor the nature of the scenarios. But we note: They do not show up in Keepin's scenariettes and particularly so when the allocation of oil and coal across world regions must be analyzed (see Chapter 17 [2], page 548 ff).

The IIASA study evaluated the features of energy demand. The method chosen was to account for the end uses of energy as these can be approached in terms of the requirements of human beings. Clearly, it is impossible to predict the prices of energy in 50 years from now and their relative ordering. It is particularly difficult to project energy demand in such world regions as Africa and Southeast Asia. But it is possible to account for the energy requirements of human beings, at least in so far as one can anticipate certain life styles. Here it was even more drastic to disaggregate and to determine thereby plausibility. Attention should be paid to the details of energy demand as given in Chapter 16 of Energy in a Finite World [2] (see in particular Tables 16-5, 16-6, 16-9, 16-10, 16-11). Some results were especially surprising. For instance, it became apparent that despite efficiency improvements and other conservation measures the provision and use of liquid fuels is a particular bottleneck and can therefore be labeled the problem within the problem. In Keepin's scenariettes the use of electricity and liquid fuel are simply used as a starting point. We ask: why not room heating or industrial uses of energy? This again illustrates the fact that there is nothing easier than a solved problem. Another aspect of the analysis concerned specific energy intensities (in Watts/dollar/yr as given in Figures 16-5 and 16-6 of [2]). They too function as a powerful tool for monitoring the consistency and plausibility of the IIASA scenarios. Again, they do not become apparent in scenariettes.

The set of IIASA models also contains the further step of the IMPACT [8] model that uses an input/output approach to determine the feedback of energy investments to the rest of the economy. In the early 1970s this was assumed to be a major factor. Indeed had not most people concluded that the rise in the oil prices had shaken the rest of the world economy. But then the analyses pointed to the effect that was labeled by Alan Manne as the rabbit and the elephant [9], the rabbit being the energy sector and the elephant the rest of the economy. They are of radically different size and it is difficult to conclude from the rabbit to the elephant. Macroeconomically this does not lead to tangible insights. If such a relationship is to be considered valid, it must be proven on a much more subtle level, which includes to a large extent a stratum of business investments, institutional behavior, and political expectations. This was outside the scope of the IIASA study. Given the fact that such feedbacks from energy to economy were macroeconomically not tangible, it made no sense to close the loop of models formally. This is one major objection of Keepin. But the IIASA study states clearly in Energy in a Finite World [2] on page 403/404:

> "Finally, a macroeconomic model could accept exogenous assumptions about demographics and institutional parameters such as productivity, taxes, and trade and could calculate the investment and consumption rates consistent with the costs from IMPACT. This could allow assessment of the magnitude of change in, for example, the capital output-ratio if and when energy becomes increasingly capital intensive. This in turn could enable both a recheck of the original estimates of GDP for each region and a reentering the iterative process. MACRO [10,11] is being revised and adapted for these purposes; it was not used in obtaining the results presented in this book."

The above described formalized iteration process would be possible for an analysis of the OECD countries. Project LINK [12] comes closest to it but does not deal with energy as a variable explicitly. But to adopt this process with energy as an explicit variable for the OECD countries as well as for the Soviet Union and the developing regions was beyond the resource capacity of the IIASA energy team. What then followed were nonformalized judgments made at the interface of the various models of the IIASA model set. In Keepin's appraisal he observes:

> "Indeed various key assumptions were no doubt modified during the course of scenario development but this was an informal undocu-

mented process carried out in the heads of the analysts rather than the systematic procedure suggested in Figure 2 [of Keepin's appraisal] and in many statements in the documentation."

We consider this a virtue, not a vice, and reply specifically as follows:

(a) We never maintained that the model loop was formally closed (see Energy in a Finite World [2], page 403/404).

(b) Obviously the documentation was good enough for Keepin to be able to evaluate the runs and to produce scenariettes.

(c) The procedure was truly systematic: it made explicit use of the results of the several strata of the study as described above.

It is important to bear in mind the sequence of events. The research activities of the first two strata were completed before the modeling work began. Thus, the inputs to the modeling exercise were determined within these strata's research activities and not as Keepin claims "tentative predictions and arbitrary assumptions that have not been carefully substantiated or tested" (Keepin's appraisal, page 53).

Within the context of the IIASA study Energy in a Finite World one purpose of mathematical modeling was to ensure calculational consistency. Keepin himself has proven the necessity of deploying mathematical models for calculational consistency. In an earlier discourse at IIASA [13] Keepin showed that the domestic coal extraction in MESSAGE for Region III (Western Europe, Japan, Australia, New Zealand, Israel, South Africa) followed neatly the maximum extraction constraint (an input to the model) over the entire 50 year study horizon. But the heterogeneous composition of Region III especially called for the specification of extraction constraints that accounted for that heterogeneity. Otherwise Australian and South African coal would have been considered entirely a domestic resource of Western Europe. Furthermore maximum coal production ceilings for Western Europe had to be determined by coal experts. The sum of these constraints combined for Region III provided only then an upper limit for domestic coal production as shown in Appendix B Table 4 (p. 60) of Keepin's paper. Coal import ceilings were patterned along similar considerations. The willingness-to-export of other regions as well as the potential transport and harbor capacities needed for handling large volumes of coal at either end of the trading regions had to be considered in determining of the actually applied numerical values. Once this painstaking exercise was completed, the calculation was indeed straightforward. Keepin calls this a simplistic transformation of assumptions into outputs. But he can claim this only after others have completed the painstaking task of quantifying the inputs for him. Indeed such modeling forces the systematic organization of otherwise overwhelming amounts of data. Then one must observe again: There is nothing easier than a solved problem.

But this is not the only argument at this point of our rebuttal. Referring again to the discourse with Keepin at IIASA concerning the robustness of the IIASA scenarios, Keepin argued that by a minor change in the levelized costs for electricity generation of Region III in favor of coal, e.g. by increasing the cost for nuclear power by a certain percent, essentially the entire gap between hydro-power and the electricity demand curve would be filled by coal. This back-of-the-envelope calculation leads to a definite misperception of the actual constraints. How can the system switch entirely to coal when in fact domestic coal production and coal imports have already reached their maximum levels? Here the levelized costs no longer matter: an expansion of coal consumption is simply infeasible given the constraints. It is these calculous checks that demonstrate the extreme usefulness of the energy models within the analysis as Keepin himself experienced.

But there are other examples of the usefulness of the IIASA models, as for instance when checking Keepin's scenariettes. In the following we concentrate on Figures 15a and 15b of Keepin's appraisal (see pages 38 to 40). Figure 15a shows the electricity generation for Region I, IIASA Low Scenario. Keepin maintains that a 16% increase in the costs of nuclear power, i.e Light Water Reactors (LWRs) and Fast Breeder Reactors (FBRs), and a simultaneous expansion of the coal extraction limit by 7% leads to an entire abolishment of nuclear generated electricity by the year 2030 (see Figure 15b). Taking this statement at face value we incorporated these modifications into the MESSAGE model and reran the Region I IIASA Low Scenario. Some 5 minutes later we obtained the model output as shown in Figure 1: Clearly, a 16% increase in nuclear costs had to show an impact on the model solution, and coal's contribution to electricity generation increased indeed. But in contrast to Keepin's calculations nuclear technologies were still part of the supply picture. According to the IIASA Low Scenario in 2030 coal-generated electricity was 51.75 GW(e)yr/yr; as Table 1 shows, in the modified scenario coal-generated electricity has increased to 382 GW(e)yr/yr at the expense of LWRs and FBRs (indeed down from 190 GW(e)yr/yr to 123 GW(e)yr/yr (LWR) and from 301 GW(e)yr/yr to 37 GW(e)yr/yr (FBR) respectively) but nuclear energy did not vanish: The expansion of nuclear from some 42 GW(e)yr of electricity in 1980 to 160 GW(e)yr (LWR + FBR) in 2030 prevailed. Thus one cannot disregard this result nor can one legitimately claim that nuclear "disappears entirely" (Keepin's appraisal, page 40).

In seeking the explanation for the striking difference between the IIASA findings and Keepin's calculations, we resolved this contradiction by analyzing Keepin's data in his Appendix E. Here Keepin's assumed modest 7% increase of the coal extraction constraint turned out to be almost 40% by 2030 (see

Table 2): The maximum extraction constraint of 2000 GWyr/yr (IIASA Low Scenario) was actually raised by Keepin to 2788 GWyr/yr, certainly not a minor change. To call a model response to a 16% increase in nuclear costs and a 40% expansion of the coal extraction constraint "structurally brittle with respect to minor changes in various assumed input data" (see Keepin's appraisal page 52) is untenable. Furthermore, to put this level of coal extraction into perspective, we note that Keepin's coal extraction level is even slightly higher than the rather optimistic upper coal extraction level of the IIASA High Scenario. In other words, Keepin disregards the economic setting of a "low growth" scenario and its implications for the development of coal mining and coal handling infrastructures. More importantly, the increase in actual coal consumption compared to the IIASA Low Scenario amounts to 71%. In terms of primary energy consumption of Region I this implies a 64% dependence on coal by the year 2030 (see Table 3 and Figure 2)!

The 7% increase in coal extraction quoted by Keepin was found to be based on cumulations of the *potential* use of coal as determined by the constraints of the IIASA Low Scenario. That is: Keepin accumulates the maximum *potential* coal production of the IIASA Low Scenario (see Keepin's appraisal Appendix E, page 136) and confronts this figure with the coal requirements of his scenariette approach. This comparison results indeed in the 7% difference. But the correct comparison should have encompassed the actual cumulative coal consumption of the IIASA Low Scenario and the coal requirements of his scenariette. In this case the difference then is striking: Keepin's scenariette requires some 70% more coal than would actually be used in the IIASA Low Scenario.

Again we reflected Keepin's modifications in MESSAGE. The results are summarized in Figure 3. Needless to say that this took some 5 minutes and produced better calculous consistency than Keepin's scenariette. In spite of his attempts to eliminate nuclear from his scenariette his arbitrary assumptions failed to do this properly: here too some 17 GW(e)yr of nuclear generated electricity survived this nuclear termination scenario. Again, we stress that such modeling forces the systematic organization of otherwise overwhelming amounts of data.

A further case in point is the competition between the FBRs and the LWRs as modeled in MESSAGE. Yes, the crossing of prices is flat, rather than steep. But this has a substantive background and is therefore not an artifact. In the first stratum, where in Chapter 4 of [2] the nuclear potential is explored, it is explained that eventually this will occur as the use of uranium resources in LWRs only would be possible through 2020 or 2030 but not much longer. Guided by the insights from other strata of the IIASA energy study, we did not want to produce formal results that would be meaningless beyond the year 2030, the end point of our formal modeling process. Thus the robustness of this energy path does not become apparent when one considers only the stratum of energy modeling separately. It is apparent, however, when the study findings are considered as a whole, as was done in Part VI of Energy in a Finite World [2].

The same reasoning applies to the problem of environmental protection. In his appraisal Keepin observes:

> "One of the robust conclusions drawn from this scenarios is that the world will consume "unprecedented amounts" of dirty fossil fuels such as tar sands and oil shales. In addition "coal use shows a tremendous increase, by as much as a factor of five" (Häfele, 1983a). It is acknowledged that such policies would entail severe consequences: "environmental problems raised to the second or third power of what we normally envisage will be involved" (Häfele, 1983a). However, as

discussed above, no explicit environmental constraints are accounted for in these scenarios. Nevertheless, this conclusion is claimed to be robust."

We respond:

Yes it is robust and is a major point of Part VI, Chapter 25 [2] where the synthesis is provided (see in particular page 804 f). But this was neglected by Keepin. It was simply not the point to make the energy modeling an image of the study results. It is just but one tool besides others.

As a matter of fact, after his return to FRG W. Häfele made it a major point at the Kernforschungsanlage Jülich to design what is called a "novel horizontally integrated energy system" and to develop it [14]. It will permit for "zero emissions" to the atmosphere and the hydrosphere and follows the idea of decomposing and thereby cleaning the mass streams of fossil fuel prior to combustion. This includes hardware such as the exogenous driven water/methane shift reaction, steam coal gasification, electrolysis and others.

Finally, let us address the heart of the issue in question. It is the old controversy "soft versus hard energy paths". Yes, we are not soft enough to suggest to the Have-Nots of the world who live currently with an average per capita energy consumption of 0.2 kWyr/yr that they can expect no more than, say, a per capita consumption of 0.6 kWyr/yr, while in North America the average per capita consumption is some 10 kWyr/yr and in Europe some 5 kWyr/yr. This is no basis for healthy global politics. We refuse to prescribe to the Have-Nots how to live, especially under these circumstances. Nor do we want to live with a per capita consumption of 0.6 kWyr/yr either. In fact, we want to give all people the energy they want and need and let them choose for themselves the way of living they like. We do not want to transform or change societies. What we want is a free development that is constrained only to a degree that is unavoidable. Indeed, with eight billion people in the year 2030, a per capita energy consumption of 2 kWyr/yr results in 16 TWyr/yr, 3 kWyr/yr results in 24 TWyr/yr, and 4 kWyr/yr results in 32 TWyr/yr. Yes, we do find an average global per capita consumption figure between 3 kWyr/yr and 4 kWyr/yr a reasonable one and this leads to the IIASA energy scenarios. It is still less than the 10 kWyr/yr of North America and the 5 kWyr/yr of Europe.

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Table 1. Region I: Electricity Generation by Technology, 1980-2030 (GW(e)yr/yr). This scenario is based on an increase in nuclear costs of 16% and a raise in the coal extraction of 7% above the IIASA Low scenario.

Year	Hydro	LWR	FBR	Coal	Advcoal[a]	Petg[b]	Solar
1980	54.87	41.93	0.	184.23	0.	33.97	0.
1985	58.92	64.75	0.	219.60	0.	17.73	0.
1990	63.37	64.10	0.	257.63	0.	19.90	0.
1995	68.34	63.54	0.	288.24	3.98	21.91	0.
2000	73.32	66.63	0.	301.52	15.90	23.63	0.
2005	78.04	48.93	0.	327.93	35.12	20.97	0.
2010	82.49	42.25	0.	312.36	79.96	20.94	0.
2015	86.66	38.26	0.	246.12	171.11	19.85	0.
2020	90.53	73.80	1.33	176.31	245.20	0.82	0.
2025	94.09	132.72	10.98	112.10	264.10	0.	0.
2030	97.09	123.61	37.28	65.34	316.68	0.	0.

[a]Advcoal stands for a new and more efficient generation of coal-fired electricity production facilities.
[b]Oil or gas-fired electricity production facilities.

Table 2. Coal Extraction in the IIASA Low and High Scenarios and Keepin's Modifications, 1980-2030 (GWyr/yr).

	Low Scenario Maximum Annual Coal Extraction	Actual Extraction	Scenariette plus 7% Maximum Extraction	Scenariette "No Nuclear" Actual	High Scenario Maximum Annual Coal Extraction	Actual Extraction
1980	650	650	696	650	650	650
1985	800	800	856	800	900	900
1990	900	815.1	963	900	1100	1048.2
1995	950	753.8	1017	950	1250	1091.2
2000	1000	685.4	1070	1000	1500	1075.1
2010	1400	476.8	1498	1245.9	1900	1102.7
2015	1600	504.2	1712	1403.1	2000	1540.1
2020	1800	712.6	1926	1703.0	2200	1819.5
2025	2000	1093.1	2140	2206.1	2400	2352.6
2030	2000	1550.3	2140	2766.7	2700	2700.0

Table 3. Region I: Primary Energy Consumption or Equivalent (GWyr/yr), 1980-2030. This scenario is based on an increase in nuclear costs of 16% and a raise in the coal extraction of 40% for the period 2025-2030 above the IIASA Low scenario.

Year	Coal	Synf	Total Coal	Gas	Crude	Hydgeo	LWR	FBR	Solren[a]	Total PE[b]
1980	650	0	650	753	641	148	113	0	8	2314
1985	800	0	800	715	780	159	174	0	16	2645
1990	900	0	900	748	880	171	185	0	24	2909
1995	950	0	950	744	97000	184	206	0	31	3087
2000	1000	0	1000	766	1065	197	247·	0	38	3317
2005	1140	1	1141	759	1090	210	198	0	45	3447
2010	1226	18	1245	760	1101	222	177	0	52	3566
2015	1305	97	1403	757	1075	233	141	0	58	3686
2020	1407	295	1703	697	972	244	129	0	64	3853
2025	1474	731	2206	699	719	254	102	0	69	4105
2030	1576	1190	2766	700	452	262	45	0	74	4235

[a] Solar and renewables

[b] Primary Energy; rows may not sum to totals because of rounding.

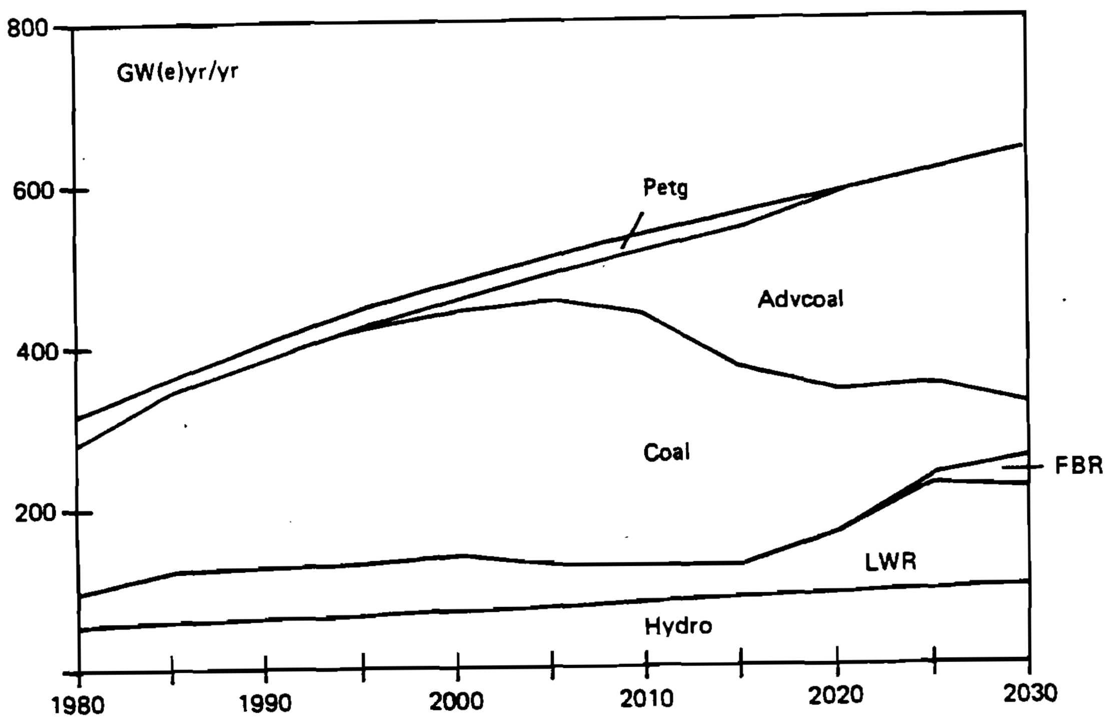


Figure 1. Region I: Electricity Generation (GW(e)yr/yr), 1980-2030.
This scenario is based on an increase in nuclear costs of 16% and a raise in the coal extraction of 7% above the IIASA Low scenario.

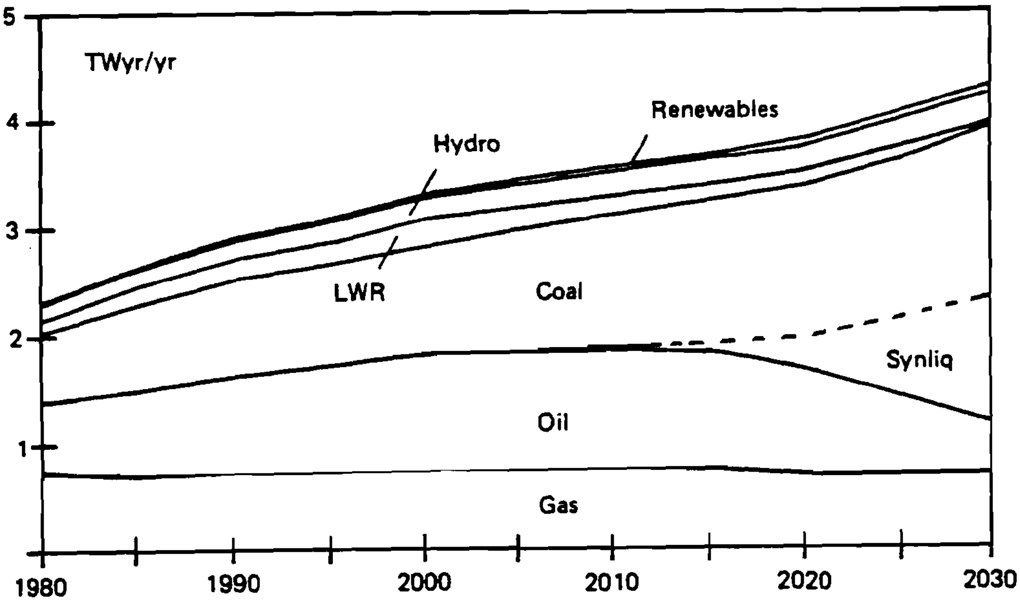


Figure 2. Region I: Primary Energy Consumption or Equivalent (TWyr/yr), 1980-2030.
This scenario is based on an increase in nuclear costs of 16% and a raise in the coal extraction of 40% for the period 2025-2030 above the IIASA Low scenario.

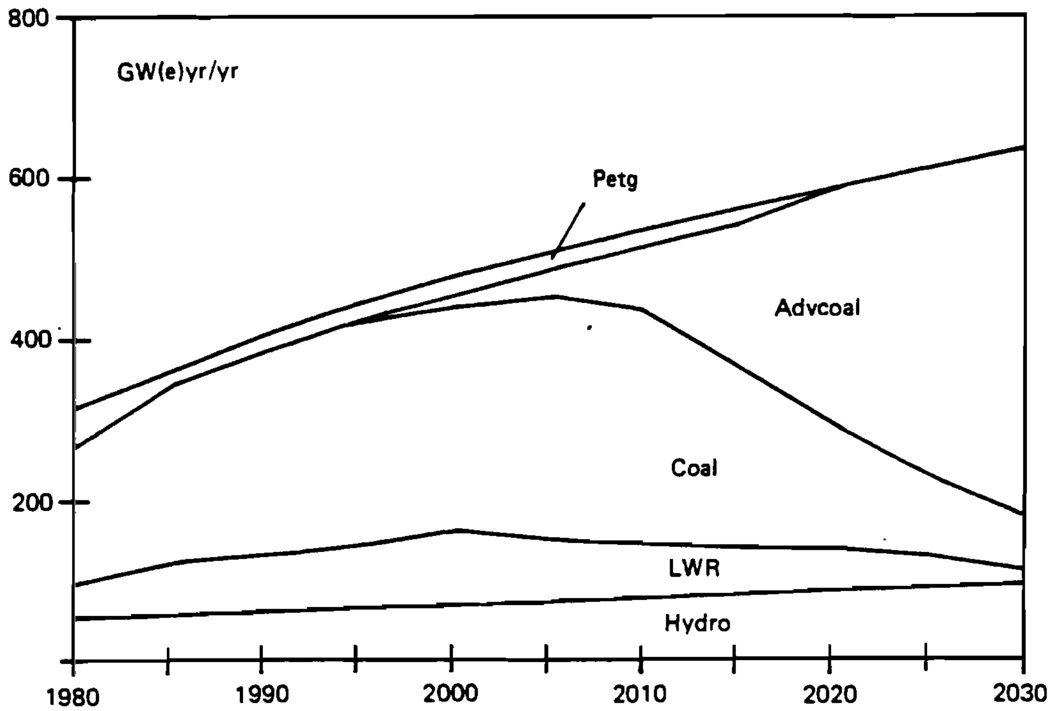


Figure 3. Region I: Electricity Generation (GW(e)yr/yr), 1980-2030.
This scenario is based on an increase in nuclear costs of 16% and a raise in the coal extraction of 40% for the period 2025-2030 above the IIASA Low scenario.

Table 15-1. Summary of scenario energy projections, final energy.

A. Final Energy for 1950 and 1975 and Projections to 2030 (TWyr/yr)

	Historical		*High Scenario*		*Low Scenario*	
Region	*1950*	*1975*	*2000*	*2030*	*2000*	*2030*
I (NA)	0.96	1.87	2.63	3.67	2.26	2.64
II (SU/EE)	0.36	1.28	2.39	4.11	2.17	2.95
III (WE/JANZ)	0.55	1.59	3.04	4.38	2.39	2.99
IV (LA)	0.05	0.26	1.01	2.64	0.73	1.66
V (Af/SEA)	0.05	0.25	1.06	3.17	0.80	1.88
VI (ME/NAf)	0.01	0.11	0.58	1.64	0.43	0.87
VII (C/CPA)	0.03	0.39	1.23	3.20	0.85	1.59
World	2.01	5.74	11.93	22.80	9.64	14.56

B. Final Energy Growth Rates for 1950-1975 and Projections to 2030 (%/yr)

	Historical	*High Scenario*		*Low Scenario*	
Region	*1950–1975*	*1975–2000*	*2000–2030*	*1975–2000*	*2000–2030*
I (NA)	2.7	1.4	1.1	0.8	0.5
II (SU/EE)	5.2	2.5	1.8	2.2	1.0
III (WE/JANZ)	4.3	2.6	1.2	1.7	0.7
IV (LA)	6.8	5.6	3.3	4.3	2.8
V (Af/SEA)	6.7	5.9	3.7	4.7	2.9
VI (ME/NAf)	10.4	7.0	3.5	5.8	2.3
VII (C/CPA)	10.8	4.7	3.2	3.1	2.1
World	4.3	3.0	2.2	2.1	1.4

Notes: These data for final energy include nonenergy feedstocks but exclude noncommercial energy such as wood, agriculture and animal waste. See Appendix 1B for the definition and conversion of energy units. Estimates of historical final energy are taken from Chant (1980). Data and world totals are rounded; totals may appear to not add exactly. Growth rates were calculated using non-rounded data and then rounded to one decimal place; these rates may therefore appear to not apply exactly in part A of the table.

SOURCE: [2].

Table 15-5. Primary energy-GDP elasticities, ϵ_p, 1950–2030.

Region	*Historical* 1950–1975	*High Scenario* 1975–2000	2000–2030	*Low Scenario* 1975–2000	2000–2030
I (NA)	1.03	0.42	0.67	0.36	0.89[a]
II (SU/EE)	0.77	0.65	0.67	0.62	0.62
III (WE/JANZ)	0.96	0.70	0.77	0.65	0.73
IV (LA)	1.28	1.04	0.98	1.06	0.97
V (Af/SEA)	1.52	1.15	1.11	1.18	1.19
VI (ME/NAf)	1.20	1.16	0.96	1.23	1.10
VII (C/CPA)	1.57	1.06	1.17	0.98	1.27[a]
World	0.99	0.70	0.90	0.67	0.93

[a]The primary energy-GDP elasticity is unusually high for regions I and VII in the Low scenario. In the later time period in these regions, demand for liquids must be met from coal liquefaction, which has significant conversion losses, thus adding to primary energy use. Since the GDP growth is small in the Low scenario, the elasticity of primary energy use with GDP is increased. If these losses are subtracted from primary energy consumption in 2030, the resulting elasticities are 0.53 and 0.94 for regions I and VII, respectively. The same effect is present in the High scenario for regions I, II, III, and VII, but is less pronounced in the elasticity because GDP growth is higher.

Note: Historical values were computed by linear regression on logarithmic transformation of equation (see note, p. 446) using five yearly data (see Chant 1980). Values for the projection period result from the scenario data.

SOURCE: [2].

Table 15-6. Final energy-GDP elasticities, ϵ_f, 1950-2030.

A. High Scenario					
	Historical				
Region	*1950-1975*	*1975-1985*	*1985-2000*	*2000-2015*	*2015-2030*
I (NA)	0.84	0.31	0.43	0.53	0.48
II (SU/EE)	0.68	0.59	0.58	0.52	0.53
III (WE/JANZ)	0.84	0.77	0.65	0.58	0.51
IV (LA)	1.21	1.07	1.01	0.97	0.90
V (Af/SEA)	1.42	1.20	1.08	1.05	1.01
VI (ME/NAf)	1.17	1.12	1.07	0.95	0.81
VII (C/CPA)	1.53	1.10	1.02	1.02	0.96
World	0.87	0.69	0.73	0.78	0.77

B. Low Scenario					
	Historical				
Region	*1950-1975*	*1975-1985*	*1985-2000*	*2000-2015*	*2015-2030*
I (NA)	0.84	0.24	0.38	0.53	0.46
II (SU/EE)	0.68	0.54	0.57	0.50	0.41
III (WE/JANZ)	0.84	0.67	0.64	0.60	0.49
IV (LA)	1.21	1.10	1.03	0.95	0.88
V (Af/SEA)	1.42	1.19	1.12	1.14	1.06
VI (ME/NAf)	1.17	1.21	1.11	1.01	0.93
VII (C/CPA)	1.53	1.02	0.98	0.99	0.90
World	0.87	0.64	0.73	0.79	0.74

Note: Historical values were computed by linear regression on logarithmic transformation of equation (see note, p. 446) using five yearly data (see Chant 1980). Values for the projection period result from the scenario data.

SOURCE: [2].

Table 15-7. Real prices for final (delivered) energy (1975 $ per kWyr).

	Industry Sector	*Transport Sector*	*Residential-Commercial Sector*	*All Sector Aggregate*
Region I (NA)				
1972	30	116	83	70
1975	52	144	108	97
1975–1972	1.73	1.24	1.30	1.35
Region III (WE/JANZ)				
1972	62	254	135	113
1975	92	338	174	159
1975–1972	1.48	1.33	1.29	1.41

Notes: $100 per kWyr is equivalent to $19.40 per barrel of oil equivalent, $3.34 per million Btu, and $0.011 per kWh. These prices are calculated from data contained in Hogan (1979). These data were taken from a data base assembled by Pindyck as described in Pindyck (1978) and updated from several sources by Hogan. Data on current prices were adjusted for inflation using a GNP deflator; currency conversions were based on a purchasing power parity conversion rate. The data reported here for region III (WE/JANZ) are for the aggregation of data for the four largest energy-using countries only: France, FRG, the United Kingdom, and Japan.

SOURCE: [2].

Table 15-9. Final energy-income and energy-price elasticities.

Region	High Scenario Income elasticity γ	High Scenario Price elasticity β	Low Scenario Income elasticity γ	Low Scenario Price elasticity β
I (NA)	(0.8, 1.0)	(−0.52, −0.81)	(0.8, 1.0)	(−0.35, −0.52)
II (SU/EE)	(0.8, 1.0)	(−0.46, −0.85)	(0.8, 1.0)	(−0.42, −0.71)
III (WE/JANZ)	(0.8, 1.0)	(−0.30, −0.66)	(0.8, 1.0)	(−0.22, −0.45)
IV (LA)	(1.1, 1.2)	(−0.23, −0.44)	(1.1, 1.2)	(−0.18, −0.35)
V (Af/SEA)	(1.2, 1.3)	(−0.24, −0.45)	(1.2, 1.3)	(−0.11, −0.27)
VI (ME/NAf)	(1.1, 1.2)	(−0.24, −0.49)	(1.1, 1.2)	(−0.02, −0.20)
VII (C/CPA)	(1.2, 1.3)	(−0.32, −0.50)	(1.2, 1.3)	(−0.30, −0.43)

Note: Final energy price elasticities are all sector aggregates for the period 1975–2030, calculated according to the equation (see footnote e) to be consistent with GDP and final energy scenario projections and with the assumed range of values for the income elasticities shown. The historical values for 1950–1975 for γ are given in Tables 15-5 and 15-6 under the assumption that real prices did not change during that period. These values are, respectively, 0.84, 0.68, and 0.84 for regions I, II, and III and 1.21, 1.42, 1.17, and 1.53 for regions IV, V, VI, and VII. The high values for the developing regions would not be particularly appropriate for the projection period; the range shown in this table would be more appropriate. Note also that the price elasticities of the High scenario are larger than those for the Low scenario, because it was implied that a higher innovation rate thus favoring more energy conservation would go along with the higher growth rates of the High scenario.

SOURCE: [2].

Table 15-11. Projected increases in payments for energy as fraction of GDP.

A. High Scenario

Region	*GDP*	*Final Energy*	*Final Energy Price*	*Payments for Energy-GDP*[a]
I (NA)	4.75	1.96	3.0	1.24
II (SU/EE)	8.23	3.25	3.0	1.18
III (WE/JANZ)	4.90	2.75	2.4	1.35
IV (LA)	10.50	10.36	3.0	2.96
V (Af/SEA)	10.26	12.56	3.0	3.67
VI (ME/NAf)	15.36	15.45	3.0	3.02
VII (C/CPA)	7.66	8.13	3.0	3.18

B. Low Scenario

Region	*GDP*	*Final Energy*	*Final Energy Price*	*Payments for Energy-GDP*[a]
I (NA)	2.50	1.41	3.0	1.69
II (SU/EE)	5.07	2.31	3.0	1.37
III (WE/JANZ)	2.79	1.88	2.4	1.62
IV (LA)	6.56	6.49	3.0	2.97
V (Af/SEA)	5.87	7.42	3.0	3.79
VI (ME/NAf)	6.90	8.19	3.0	3.56
VII (C/CPA)	4.20	4.04	3.0	2.89

[a]Projected energy payments as a fraction of GDP in 2030 relative to energy payments as a fraction of GDP in 1975 using 1972 energy prices. For example, if energy consumption doubles and price triples, then energy payments increase sixfold. But if GDP also increases fourfold, then this "payments for energy-GDP" index would be 6/4 = 1.50.

Notes: Values given are for the year 2030 as a multiple of base year value. GDP and final energy are given as projected 2030 values relative to 1975 values. Price increase is for final energy (delivered to the user) relative to 1972 price levels.

SOURCE: [2].

Table 16-5. Household use of electricity, 1975 and scenario assumptions (10^3 kWh/household).

Region	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA) total electricity	9.4	13.0	15.0	11.9	12.9
(% thermal uses)[a]	(59)	(52)	(47)	(56)	(52)
II (SU/EE) total electricity	1.2	3.9	6.5	3.0	4.3
(% thermal uses)	(25)	(26)	(23)	(29)	(30)
III (WE/JANZ) total electricity	3.1	6.0	9.1	5.3	7.1
(% thermal uses)	(38)	(39)	(34)	(38)	(36)
IV (LA) total electricity	0.7	1.9	4.2	1.4	2.7
(% thermal uses)	(3)	(11)	(20)	(13)	(21)
V (Af/SEA) total electricity	0.05	0.2	0.5	0.1	0.3
(% thermal uses)	(1)	(4)	(8)	(3)	(11)
VI (ME/NAf) total electricity	0.2	1.2	4.3	0.9	1.8
(% thermal uses)	(9)	(22)	(23)	(19)	(33)

[a] Thermal uses include air conditioning.

Notes: Only for region I (NA) were sufficient statistics available; for other regions estimates come from partial data and/or data for selected countries. Consumption of electricity per household for specific uses (lighting, electrical appliances) is a direct assumption; consumption for thermal uses results from separate assumptions on useful energy consumption for space heating, water heating, cooking, and air conditioning and from assumed penetration of electricity into these markets.

SOURCE: [2].

Table 16-6. GDP sectoral shares assumptions (percentage of GDP).

Region	1975			High Scenario 2030			Low Scenario 2030		
	Agriculture	*Industry*[a]	*Service*	*Agriculture*	*Industry*[a]	*Service*	*Agriculture*	*Industry*[a]	*Service*
I (NA)	2.8	32.4	64.8	1.5	29.0	69.5	2.0	32.2	65.8
II (SU/EE)	10.7	50.3	39.0	4.0	41.0	55.0	7.0	43.0	50.0
III (WE/JANZ)	5.8	45.7	48.5	2.5	39.5	58.0	3.0	42.0	55.0
IV (LA)	12.2	35.5	52.3	4.6	47.0	48.4	6.5	43.0	50.5
V (Af/SEA)	36.1	25.5	38.4	16.2	38.2	45.6	23.2	34.8	42.0
VI (ME/NAf)	7.0	66.0	27.0	2.3	46.7	51.0	4.0	54.4	41.6

[a] Industry includes manufacturing, mining, construction, and energy sectors.

Sources of data for the base year (1975): regions I, II, and III–United Nations (1977c); regions IV, V, and VI–United Nations (1977b); and data on various region VI countries supplied by the Arab Fund for Economic and Social Development, Kuwait.

SOURCE: [2].

Table 16-9. Projected passenger travel (intercity and urban) and assumed distribution, High scenario.

	1975					*2000*					*2030*				
	Activity level (10^{12} pass km)	*Modal split (%)*				*Activity level (10^{12} pass km)*	*Modal split (%)*				*Activity level (10^{12} pass km)*	*Modal split (%)*			
Region		*Plane*	*Car*	*Train[a]*	*Bus*		*Plane*	*Car*	*Train[a]*	*Bus*		*Plane*	*Car*	*Train[a]*	*Bus*
I (NA)	4.1	4	93	1	2	6.2	12	83	2	3	8.2	20	73	3	4
II (SU/EE)	1.7	11	26	51	12	4.0	13	29	45	13	6.4	15	30	41	14
III (WE/JANZ)	5.2	3	37	37	23	9.2	9	44	27	20	13.8	12	50	20	18
IV (LA)	1.3	1	37	5	57	4.3	3	45	5	47	10.7	4	49	9	38
V (Af/SEA)	1.5	1	25	14	60	5.2	2	32	11	55	16.4	2	39	10	49
VI (ME/NAf)	0.3	1	29	5	65	1.6	2	34	9	55	5.6	4	38	15	43

[a] Train includes urban electric mass transit.

Sources of data for 1975: United Nations (1977c); International Road Federation (1973, 1976); *The Middle East and North Africa, 1974-1975* (1976); CMEA (1976).

SOURCE: [2].

Table 16-10. Assumptions for automobile ownership and usage in six world regions.

	Base Year 1975	*High Scenario*		*Low Scenario*	
		2000	*2030*	*2000*	*2030*
A. Auto Ownership (auto/1000 pop)					
Region:					
I (NA)	500	526	526	526	526
II (SU/EE)	25	63	100	50	67
III (WE/JANZ)	192	305	450	240	313
IV (LA)	39	100	230	72	144
V (Af/SEA)	4	11	38	9	22
VI (ME/NAf)	17	59	177	42	79
B. Intercity and Urban Distance Traveled (10^3 km/auto/yr)					
Region:					
I (NA)	15.9	16.1	16.5	15.9	15.9
II (SU/EE)	18.5	17.1	17.6	16.2	16.5
III (WE/JANZ)	9.2	10.2	10.3	10.1	9.9
IV (LA)	13.2	13.8	13.1	15.4	15.0
V (Af/SEA)	25.2	21.3	19.3	24.4	26.0
VI (ME/NAf)	16.4	16.6	18.1	19.3	24.4

Sources of data for 1975: United Nations (1977c); International Road Federation (1976); U.S. Department of Commerce (1976).

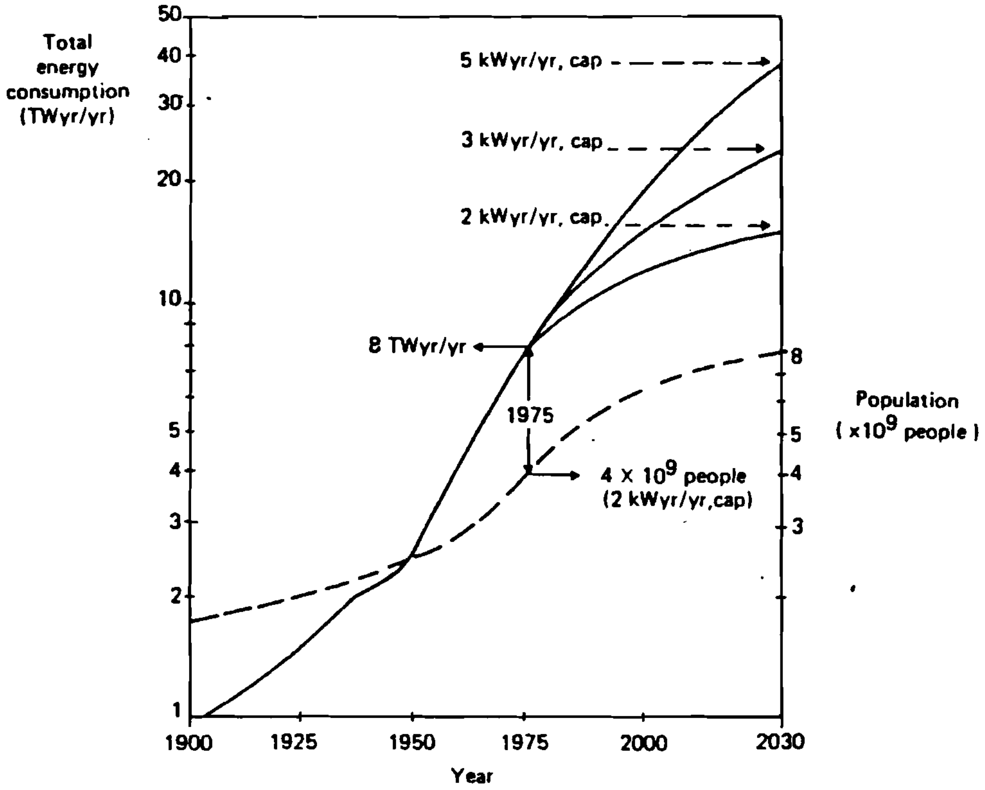
SOURCE: [2].

Table 16-11. Energy use by automobiles in six world regions.

Region	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA)					
Energy used by cars (GWyr/yr)	364	205	194	203	201
As share of total transportation energy (%)	(67)	(32)	(19)	(36)	(29)
II (SU/EE)					
Energy used by cars (GWyr/yr)	26	45	63	42	50
As share of total transportation energy (%)	(11)	(11)	(8)	(11)	(9)
III (WE/JANZ)					
Energy used by cars (GWyr/yr)	111	214	249	168	179
As share of total transportation energy (%)	(35)	(30)	(22)	(32)	(26)
IV (LA)					
Energy used by cars (GWyr/yr)	20	82	238	67	179
As share of total transportation energy (%)	(19)	(20)	(21)	(22)	(25)
V (Af/SEA)					
Energy used by cars (GWyr/yr)	17	67	277	60	216
As share of total transportation energy (%)	(22)	(25)	(30)	(27)	(36)
VI (ME/NAf)					
Energy used by cars (GWyr/yr)	6	27	108	22	67
As share of total transportation energy (%)	(13)	(13)	(18)	(16)	(21)

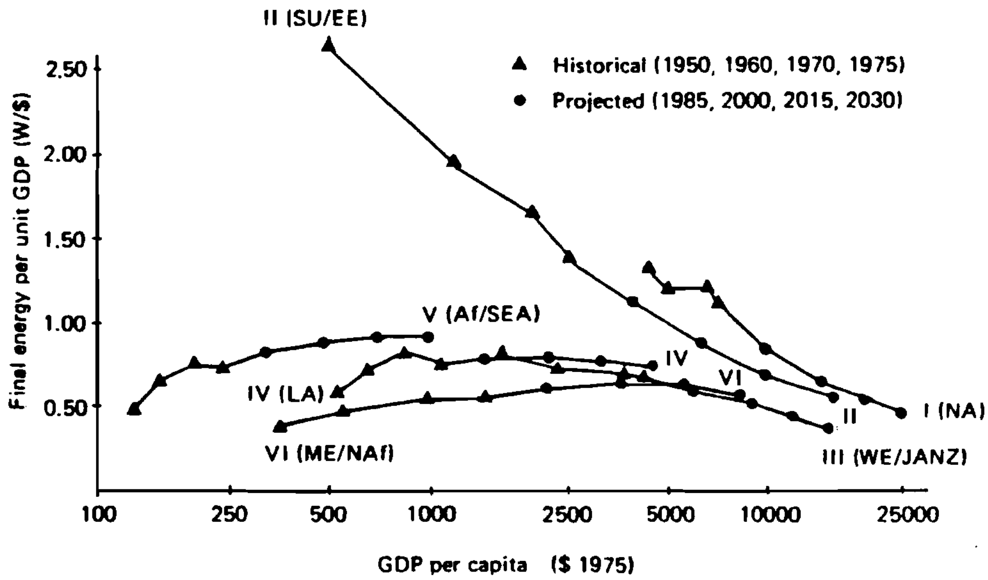
SOURCE: [2].

Figure 1-5. Total energy consumption, 1975-2030: three possibilities. The solid lines indicate energy consumption; the dashed line indicates world population.



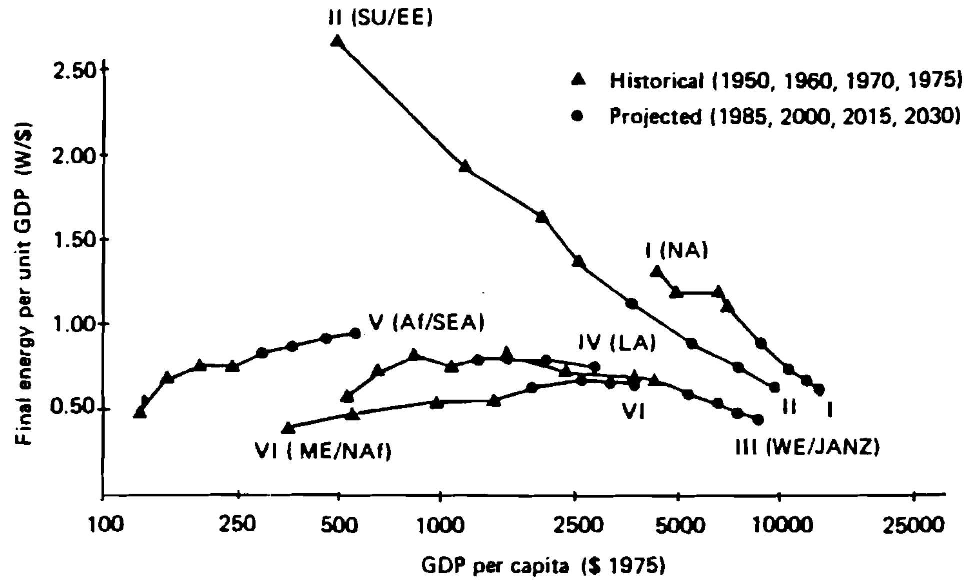
SOURCE: [2].

Figure 16-5. Energy intensiveness in different world regions, High scenario.



SOURCE: [2].

Figure 16-6. Energy intensiveness in different world regions, Low scenario.



SOURCE: [2].