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A CRITICAL APPRAISAL OF THE IIASA ENERGY SCENARIOS

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PREFACE

The energy developments of the last decade stimulated many scientific studies of the global energy system and its possible future evolution. One of the most extensive of these studies was carried out by IIASA's Energy Systems Program between 1973 and 1980, culminating in the final report, *Energy in a Finite World*. An important aspect of the IIASA work involved the development of mathematical models for the purpose of analyzing possible transitions from the present dependence on fossil fuels to future sustainable energy systems.

In 1981 I came to IIASA to study the energy models developed here, focusing in particular on their impressive application to the global energy system published in *Energy in a Finite World*. However, as the work progressed, I came across a number of troubling aspects that eventually led me to terminate the work I was doing and investigate further. This paper is the result of that investigation, and I offer it in the hope that it will contribute to maintaining standards of high quality in future scientific work.

Many persons have helped me a great deal in this work, only a few of whom can be mentioned here. I owe the greatest debt to Valerie Jones, who provided tremendous support, encouragement, and much needed assistance. In addition, I am grateful to Brian Wynne and Mike Thompson for many hours of discussion and general encouragement. Finally, I wish to thank Rhonda Starnes and Bonnie Riley for carefully preparing the manuscript, and my sister Mavis for painstakingly proofreading the tables.

Bill Keepin

CONTENTS

LIST OF TERMS AND ABBREVIATIONS

ACT	Advanced coal technology (fluidized bed)
AS_i	Alternative scenario (subscript indicates a particular sensitivity test)
DOGR	*Documentation of the Global Runs*, a volume documenting the IIASA energy models (ESP, 1982)
EIFW	*Energy in a Finite World*, the final report of the IIASA energy study (Häfele, 1981a)
FBR	Fast breeder reactor
GFS	Gas fired steam
GT	Gas turbine
GW	Gigawatt (10^9 watts)
H-M	Häfele-Manne model (forerunner of MESSAGE)
hydro	Hydroelectric power
IIASA	International Institute for Applied Systems Analysis
IMPACT	Economic impacts model (input/output)
IS_i	Original IIASA scenario (subscript indicates a particular sensitivity test)
kt	Kilotonnes (thousand metric tonnes)
LFP	Liquid fuel power
LP	Linear programming
LWR	Light water reactor
MEDEE-2	Energy demand model
MESSAGE	Energy supply model (LP)
MMI	The set of IIASA energy models (MEDEE-2, MESSAGE, IMPACT)
MW	Megawatt (10^6 watts)
PCT	Present coal technology (with limestone scrubber)
PETG	Petroleum and gas
region I through VII	Partition of the world into seven regions (Figure 1)
scenariette	Projection of future energy system, obtained directly from assumed exogenous *inputs* to MMI
scenario	Projection of future energy system, obtained as final *outputs* from MMI (and published in EIFW)
STEC	Solar thermal electric conversion
t	Metric tonne
TW	Terawatt (10^{12} watts)

Our interest in conclusions has been so great that the method of reaching them has been neglected: it mattered little how much prejudice or blind acceptance of authority was connected with them, so long as they were understood and remembered.

— F.M. McMurry, 1909

ABSTRACT

This paper presents some disturbing findings about one aspect of a major scientific study of the world's energy system. The final report of the seven-year study was published in 1981, entitled *Energy in a Finite World*. Although the study claims to provide an objective, factual analysis for political decision making, some of the major conclusions are not scientifically justified. Principal results include detailed projections of the world's energy supply systems for the coming half-century. These were produced from an apparently sophisticated set of iterative computer models. However, the models are found to be largely trivial, because their final outputs are nearly identical to their inputs, which are arbitrary, unsubstantiated assumptions. Furthermore, despite claims of robustness, the energy supply projections are found to be highly sensitive to minor variations in data that are well known to be uncertain. The sizeable contribution from the nuclear fast breeder reactor (FBR), is due to a 2% cost advantage that is introduced 25 years from now. Since future energy costs are highly uncertain, cost-minimization linear programming models are unsuitable for describing robust energy supply futures.

In addition to these analytic findings, some aspects of the work are improperly presented in the published documentation. In one case, the important role of the FBR is traced to undocumented input data. Frequent statements that the computer models formed an iterative loop are contradicted elsewhere. Preliminary work that revealed serious difficulties with robustness is not cited, and standard sensitivity tests are not included. Nevertheless, several "robust" conclusions have been drawn from the projections and widely publicized. One of these implies that nuclear power plants must be built at the average rate of one plant every few days for the next 50 years.

The overall conclusion in this paper is that the energy supply projections are opinion, rather than credible scientific analysis, and they therefore cannot be relied upon by policy makers seeking a genuine understanding of the energy choices for tomorrow.

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1. INTRODUCTION

In the wake of the first oil price shock in 1973, just as "the energy problem" was catapulted into the limelight as a major international issue, a comprehensive study of the global energy system was initiated at the International Institute for Applied Systems Analysis (IIASA). The study lasted for more than seven years, and involved over 225 person-years of effort, with a research budget of some $6.5 million.* As described in a review of recent energy studies, the IIASA work "is the most ambitious such study carried out thus far" (Perry, 1982). In addition to the 60-odd research reports and various conference proceedings that were produced, the final report of the study is documented in a two-volume set entitled *Energy in a Finite World* (Häfele, 1981a). The first of these (Vol. 1, 225 pages), subtitled *Paths to a Sustainable Future*, is for the general reader, providing descriptions of the various aspects of the

* See Appendix A

study and the associated findings. The second volume (Vol. 2, 850 pages), subtitled *A Global Systems Analysis*, is the full technical report which is intended for energy specialists and the interested scientific community. In addition, a 60-page *Executive Summary* (McDonald, 1981) has been widely distributed, and various magazine articles have been published in such journals as *Science*, *Scientific American*, *Futures*, *The Energy Journal*, etc. Although this paper draws on all of these sources, the most important reference is the full technical report, *Energy in a Finite World*, Volume 2. This book is hereafter abbreviated to EIFW.

More than 140 scientists came to IIASA for periods of various lengths to participate in the study, including "economists, physicists, engineers, geologists, mathematicians, psychologists, a psychiatrist, and an ethnologist" (EIFW, p. xvi). This multidisciplinary group came from 20 different countries, encompassing not only East and West, but developing countries as well. As stated in *Science*, "an explicit attempt was made to incorporate as many views and to be as objective as possible" (Häfele, 1980a). In addition, some 34 institutions, organizations, and industrial firms supported or cooperated in some way with the project, including international organizations such as the United Nations Environment Programme (UNEP) and the International Atomic Energy Agency (IAEA). Cooperating research institutes in the United States included the National Center for Atmospheric Research (NCAR), the Electric Power Research Institute (EPRI), and the Stanford Research Institute. Further supporting and/or cooperating organizations included the Nuclear Research Center Karlsruhe (FRG), Volkswagen Foundation (FRG), Federal Ministry of Research and Technology (FRG), the Meteorological Office (UK), the National Coal Board (UK), the Austrian National Bank, and the Siberian Power Institute (USSR).

The above information is provided to give some idea of the size and scope of the energy studies carried out over a period of several years at IIASA. This is important because the sheer magnitude of the project contributes (both explicitly and implicitly) to the authority and credibility of the main conclusions of the study. This paper focuses on two hypothetical "scenarios" of the world's energy future that were developed as part of the IIASA Energy Program. The importance of these scenarios lies in the fact that they are the basis for many widely publicized conclusions drawn from the study.

The principal argument developed in this paper is that the quantitative analysis behind the scenarios does not scientifically support the conclusions drawn from them, and that these conclusions are more accurately described as opinions rather than findings. There are two major analytical results established in this paper that support this claim. First, the complex computer models used in the quantitative analysis do not play a significant role in determining the final numerical results of the scenarios. Instead, these results are nearly duplicates of various unsubstantiated assumptions and arbitrary judgments that were supplied as inputs to the mathematical analysis. Second, the scenarios are seriously lacking in robustness with respect to minor variations in certain input data. Although this lack of robustness was apparently recognized in early sensitivity studies, the later publications and final reports do not cite the early sensitivity work, nor do they include standard sensitivity analyses.

This study focuses only on the quantitative scenarios themselves, which constitute just one aspect of the IIASA energy study as a whole. Because this paper develops a strongly critical point of view with respect to *this particular aspect* of the study, some very important caveats must be clearly understood from the outset. First of all, many, if not most of the 140 scientists who participated in the study had little or no direct involvement with the formulation of the scenarios or the conclusions drawn from them. In fact, a good number of these participants disagree (some very strongly) with the methods used to develop the scenarios and/or the conclusions drawn from them. In addition, many of those who did work with the scenarios were involved in aspects that are totally unrelated to the results presented here.* Finally, much of the IIASA energy work was unrelated to, or only distantly connected with the scenarios (e.g. the logistic substitution model).

Thus it cannot be overstated that this paper addresses only one aspect of the IIASA energy study, and it is definitely *not* a general criticism of the entire program. In fact, the program contributed in many important ways to a more complete understanding of many aspects of the global energy system. It was the first serious attempt to systematically account for, and gather consistent data from all regions of the world with roughly equal emphasis. Given the magnitude and complexity of the global energy system, this was no simple task. A genuine attempt was made to properly incorporate all nations on earth, which required painstaking analysis and aggregation of masses of detailed economic, geographical, demographic, and resource data from countless sources. Furthermore, a great deal of effort went towards studying the global potential of each major source of energy. In addition, the program produced some very significant contributions, such as the outstanding empirical results obtained by Marchetti and Nakicenovic (1979) with the logistic substitution model. Finally, perhaps the most important contribution has been the innumerable personal and working relationships, interactions, and contacts that developed at IIASA, and as a result of the many conferences and workshops that were held. Indeed, the international setting and the many different cultures that

* Examples are the IIASA work on carbon dioxide and solar energy.

were represented provided a richly stimulating and highly challenging environment in which to conduct a major scientific research program on a topic as broad and politically charged as the world's energy system.

It is difficult to assess how much of the energy work at IIASA was devoted to the development of quantitative scenarios and the analysis behind them. According to EIFW, "the work took more than two years of intensive effort" (p. 391). In any case, the scenarios are unquestionably a crucial aspect of the study, as revealed by the emphasis they are given in the published documentation. Of the 850 pages in EIFW, 300 are devoted to the scenarios. In addition, half of the *Executive Summary* is focused on them, and a 570-page volume is available which is entirely devoted to the mathematical models used to produce the scenarios (ESP, 1982). Finally, the scenarios are the principal focus of "speech upon speech" (Häfele, 1983a) as well as magazine articles summarizing the IIASA energy study published in *Science*, *Scientific American*, and *Futures*. The scenarios are not intended as predictions, but rather as "indicators"; nevertheless, several "robust conclusions" (Häfele, 1983b) or "robust observations" (Häfele, 1983a) are drawn from them. This suggests that the underlying analysis is robust with respect to uncertainties in the many founding assumptions, and that a broad range of plausible energy futures is encompassed by the scenarios.

The analysis in this paper does not assess the realism or implications of most of the basic assumptions in the scenarios (such as the economic growth assumptions). In addition, this paper does not take a stand for or against any particular energy policy, especially as regards controversial matters such as the future role of nuclear or solar energy. Rather, the purpose of this work is to assess the scientific integrity of the analysis behind the IIASA energy scenarios. An earlier critique explored the significance of many of the basic assumptions and methods (Lovins, 1981). Another critique focused on the energy models themselves (Meadows, 1981), but the analyst did not have access to the detailed documentation that is now available.

Section 2 provides a brief description of the IIASA energy models as represented in the documentation. Section 3 explores the role of these models in generating the scenarios from the input assumptions, and the principal finding is that the models are largely superfluous. This is followed in Section 4 by an investigation of the sensitivity of the scenarios to certain input data that are known to be uncertain, and the finding is that the scenarios are inherently unstable with respect to small variations in these data. These results are then partly explained and clarified in a general discussion of the models presented in Section 5, which is followed by the conclusions in Section 6. Finally, a comprehensive set of appendices is included. These are specifically intended to provide sufficient documentation for the reader to reproduce the results presented and discussed in the text. Thus, although the computations are not difficult, some of the appendices are long and often tedious, but this could not be avoided.

2. DESCRIPTION OF THE IIASA ENERGY SCENARIOS

This section provides a brief description of the IIASA energy scenarios and the mathematical models that were used to generate them. The information presented here is drawn from several sources, including a 570-page document entitled *The IIASA Set of Energy Models: Documentation of the Global Runs* (ESP 1982), which contains innumerable details concerning the models and numerical data. This volume is hereafter abbreviated to DOGR.

The overall purpose of the IIASA energy study was "to understand the factual basis of the energy problem, that is, to identify the facts and conditions for any energy policy" (Häfele, 1980a). This was done in an attempt "to provide decision- and policy makers with the information they need to make strategic choices" (EIFW, p. 800). The principal means for doing this was via quantitative analysis in the form of detailed scenarios describing how the global energy system might evolve over the next 50 years. "For our quantitative analysis, we had to be realistic and pragmatic; otherwise we would not have been able to achieve the factual basis on which to consider possible longer term solutions" (EIFW, p.xiv).

Of course the future is uncertain, and therefore two scenarios were developed: a "high" scenario, which assumes high economic growth, corresponding to high energy consumption; and a "low" scenario, which presumes somewhat restrained economic growth, resulting in lower energy consumption. As described in EIFW, "Two scenarios (the High and the Low) are constructed as a means of spanning the conceivable evolutions of global energy systems over the next 50 years" (p.565). The scenarios are not intended to be forecasts or predictions, but rather to be comprehensive and internally consistent analyses from which "robust conclusions" (Häfele, 1983a) about the world's energy future may be drawn and communicated to policy makers and energy specialists.

The IIASA energy scenarios were generated with a set of three computer models for the demand, supply, and capital investment sectors of the global energy system. For this purpose the world was divided into seven regions (labeled I through VII) as shown in Figure 1, and scenarios were developed for each region individually. In each case, "high" and "low" scenarios were developed for each region, making a total of 14 regional scenarios. The individual results from the seven regions were then aggregated to yield high and low scenarios for the entire globe. International trade of resources such as Mid-East oil, was handled on an interregional basis.

2.1. The Model Loop

The set of mathematical models and related procedures that were used to develop the IIASA regional scenarios are illustrated schematically in Figure 2. This figure, which has been widely publicized, is a duplicate of Figure 13-1 of EIFW (p. 401). The formal mathematical models are designated by boxes with heavy borders in the figure, and the "assumptions, judgments, and manual calculations" are indicated by ovals with thinner borders. The major flows of information are indicated in the figure by solid arrows for direct flows, and dashed arrows for feedback flows. Note that this flow of information circulates in a clockwise fashion, which is why this is called a model *loop*. This is important, because it means that the three models are not just used in simple succession, but rather they are used *iteratively*, with the flow of information circulating around and around until an internally consistent scenario is obtained. This model loop is applied to each world region separately, with the globally unifying element being the manual procedure for "Interregional Energy Trade". Note that the term "scenario", as it is used here, does not simply mean a hypothetical conjecture about the future. Rather, it refers to the

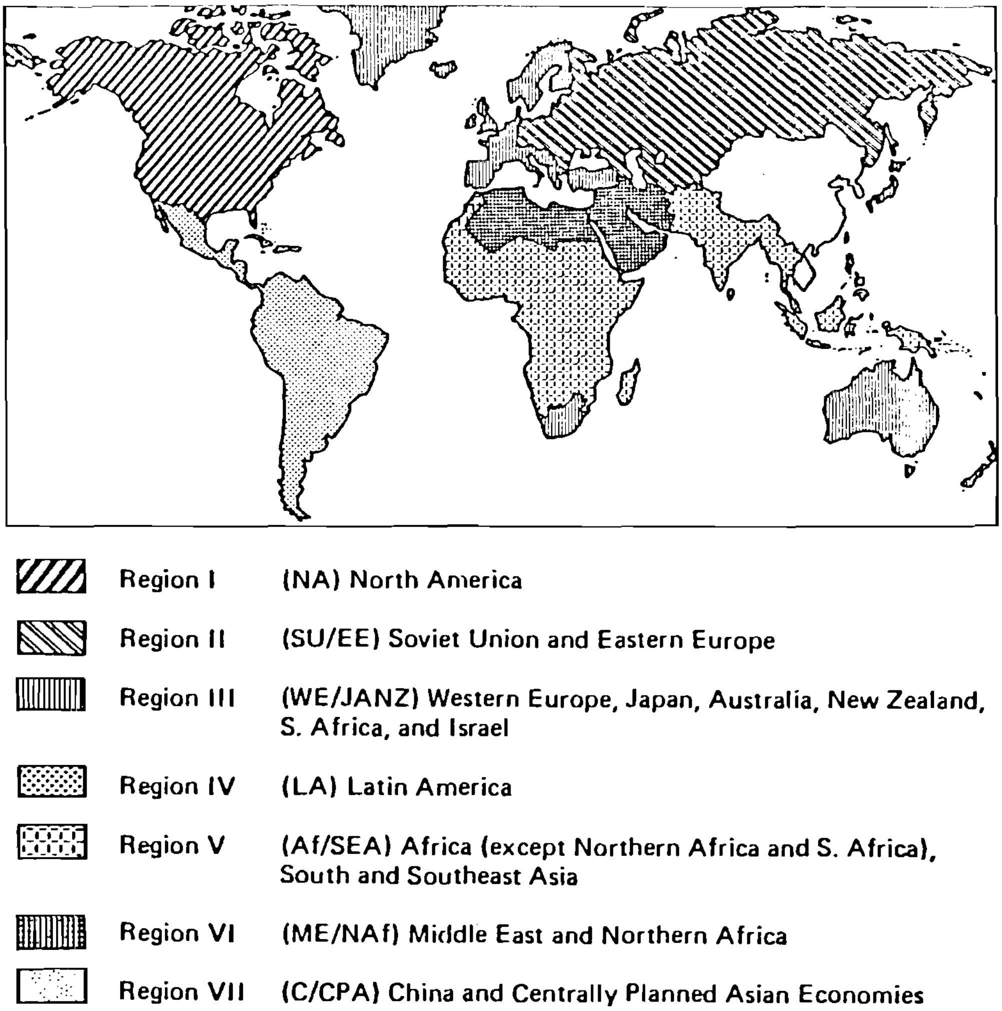

FIGURE 1 The IIASA world regions (reproduced from Figure 1–3 in EIFW, p. 11).

final quantitative results of a comprehensive mathematical analysis.

Only a brief description of the IIASA energy models will be given here — for further detail the reader is referred to EIFW and DOGR. "Logically, the description of a loop of consistent subscenarios could set out with any of its parts" (DOGR, p. viii). Thus the description of the model set can begin anywhere — I begin with the energy consumption model, MEDEE-2. This is a static accounting model which combines basic assumptions about population and economic growth with a large array of assumptions about lifestyles, require-

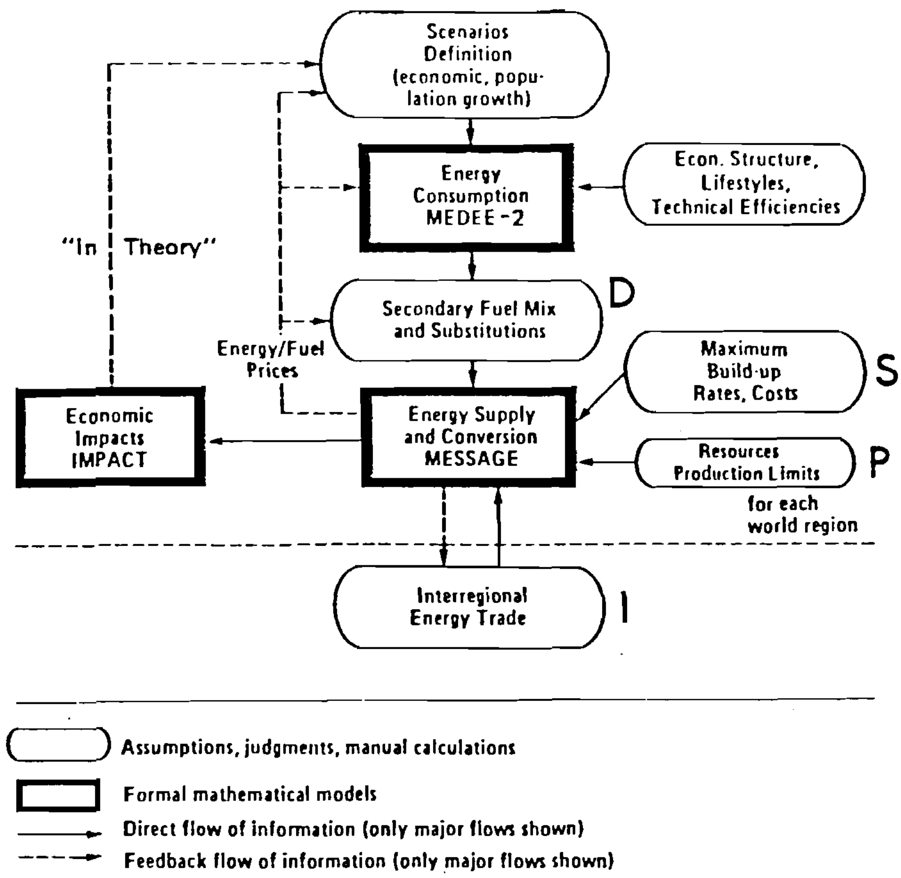

FIGURE 2 The widely publicized representation of the IIASA set of energy models, abbreviated MMI in the text (reproduced from EIFW, Figure 13–1). The capital letters (D = demand; S = secondary; P = primary; I = imports) and the words "In Theory" have been added as discussed in the text.

ments for energy services, technical efficiencies of energy-using devices, etc., to produce profiles of final energy demand from 1980 to 2030. In all, several thousand coefficients and parameters are required for the full specification of the 14 regional scenarios. The major output is a time series projection of final energy demand by sector and fuel type. Note that this demand is not the standard "demand curve" from economics, but rather a projection of future requirements for energy as a function of time. This is then converted to a demand for secondary energy (also a time series), the principal components of which are requirements for electricity and liquid fuels. This secondary energy demand is then furnished as an input to MESSAGE, the energy supply model.

MESSAGE is a dynamic linear programming model that minimizes the total discounted cost of fulfilling a given secondary demand, subject to a variety of constraints on resources and technologies. Thus, under several exogenous assumptions about availability of resources, costs and build up of technologies, etc, MESSAGE computes the optimal (i.e., least-cost) energy supply strategy for the next 50 years that fulfills the energy demand specified by MEDEE-2. Notice that this is not an economic equilibrium model; in the IIASA study, the terms demand and supply refer to the consumption and production of energy, respectively, as functions of time. Each run of MESSAGE requires the specification of some 1600 constraint variables and 2600 activity variables (Meadows, 1981), although many of these are simply zero, or constant across different regions and scenarios (Basile, 1981). The outputs from MESSAGE include the marginal costs (shadow prices) of supplying secondary energy, which are fed back to MEDEE-2, resulting in a sub-loop iteration that adjusts supply and demand. The major outputs from MESSAGE are then fed into IMPACT, the economic model.

IMPACT is a dynamic input-output model which assesses the overall economic consequences of the energy strategy spelled out by MESSAGE. Specifically, the model calculates the direct and indirect requirements for capital investment, land, water, materials, manpower, equipment, and additional energy. These variables are then fed back to modify the original assumptions about the overall development of the economy: "after a first round of model runs, the built-in feedback mechanism changed the original assumptions so there is no real 'beginning' of the model loop" (Schrattenholzer, 1981). Thus, "the main model loop is closed with IMPACT" (DOGR, p. ix), and the resulting updated economic growth assumptions are supplied to MEDEE-2, leading to corrected estimates of final energy demand (Kononov and Por, 1979, Figure 1).

The flow of information has now returned to the original starting point, completing the description of one full iteration of the main model loop. The entire process is now repeated several times until an internally consistent scenario is obtained. Since there are three models in the loop, each of which addresses a different facet of the energy system, a balanced scenario is expected from this process, as the outputs from each model are adjusted and corrected by the other two models.

As explained in EIFW, this procedure is not yet fully streamlined and computerized — most of the feedbacks are manual and the interfaces between the models are not completely formalized, leaving room for "judgmental interventions" at various stages. But this does not weaken the formalized iterative process itself (Häfele, 1980b). As stated in EIFW, "the flow of information is mechanized" (p. 400), and the streamlining is currently in the process of being developed (Häfele, 1982).

In summary, "the global High and Low scenarios are the results of applying the model loop iteratively until satisfactory consistency was achieved" (DOGR, p. x), which in turn "required several iterations of the model set" (McDonald, 1981).

3. ANALYSIS OF THE IIASA ENERGY MODELS

Models should be designed for gaining insight and understanding ...

— *Energy in a Finite World*, Vol. 2, p. 399

In this section, a rather disturbing result is established. Starting with the input assumptions to the IIASA energy models, a greatly over-simplified analysis of future energy supply is carried out (using only a hand calculator). Although this paper-and-pencil analysis entails no equations or dynamic processes, it turns out to reproduce the IIASA energy supply scenarios almost exactly. The unavoidable conclusion is that the major dynamic results of the scenarios are essentially prescribed in the input assumptions themselves, and the apparently extensive analysis performed by the models is equivalent to a back-of-the-envelope calculation. In fact, in many cases, the energy models serve as a simple identity transformation from the inputs to the outputs.

3.1. The Analytic Approach

We begin the analysis by giving thought to which results from the IIASA energy scenarios are most important. Recall that the time scale for the IIASA study is 50 years; with a time span of this length, the most one can hope for from any model is to discern major dynamic behavior patterns, and possibly their interrelationships. For this reason we will not consider most of the innumerable details contained in the scenarios. Instead, we concentrate on major dynamic variables. In particular, we will restrict our attention to primary and secondary energy flows (and their costs), since these are the principal focus of MMI. Thus, apart from energy costs, most economic considerations are excluded from this analysis, as are all aspects of the energy system that either played minor roles (e.g., solar and most renewable resources, conservation measures), or were omitted altogether from the MMI analysis (e.g., social and political factors, explicit environmental considerations).* In addition, "the analytic approach adopted for energy studies at IIASA assumes an essentially surprise-free world — no global-scale disasters, no sweeping scientific discoveries". (EIFW, p. 395). We shall do the same.

The particular energy forms to be considered are the following:

- *Primary energy* (extraction of resources): oil, coal, natural gas, and uranium.
- *Secondary energy*: electricity generation, and liquid fuels.

(Note that natural gas can be placed in either category).

The analysis presented here is carried out in greatest detail for one particular world region, comprising Western Europe, Japan, Australia, New Zealand, and South Africa (called region III in EIFW; see Figure 1). This region was chosen for several reasons, one of the most important being that it is the only region for which the iterative process of MMI is described in EIFW (pp. 404-407). In addition, the available data for this region are excellent and voluminous. Finally, region III contains the homelands of virtually all the scientists who developed the demand and supply components of the model loop (MEDEE-2 and MESSAGE).† The model's structure and principal assumptions are therefore particularly suited to this region (and most subsequent work with the model has involved applications within region III). Thus if the value of the model is called into question for region III, it is likely to be even less useful for the other six world regions. In any case, a number of results are included for other

*Some of these aspects were considered by the IIASA group ***outside*** of the formal MMI analysis. For example, the global emission and concentration of carbon dioxide that might result from the scenarios was analyzed in considerable detail (see EIFW).
†MEDEE was originally developed by two French scientists for application to France, and then later adapted for use in the IIASA model loop. MESSAGE is a third- or fourth-generation offspring stemming from an early linear programming model conceived by W. Häfele (FRG) and Alan Manne (USA). Subsequent versions were developed by scientists from Europe and Japan (both in region III).

world regions as well, including region I (USA and Canada), region V (South and Southeast Asia, and sub-Saharan Africa excluding South Africa), and the oil trading regions in aggregate.

In this analysis, the model loop will be treated as just *one* model, or black box, about which nothing is known except the inputs, the outputs, and the demand for secondary energy. Thus I will not delve into the mathematical details of the individual models themselves.* The model loop will be referred to as MMI (which stands for MEDEE-2, MESSAGE, IMPACT, and their various interlinkages), or else just simply as the model. In addition, the terms "assumptions" and "input assumptions" refer to various parameters, time series data, cost coefficients, etc., that are supplied as exogenous inputs to MMI. These are indicated in Figure 2 by the ovals labeled P (primary), S (secondary), and I (imports). The secondary energy demand is indicated by the oval labeled D in Figure 2. In the present analysis these endogenous demand projections are taken as given; therefore, this work is focused only on the supply side of the scenarios. Finally, the outputs from MMI are simply the scenarios themselves.

The numerical data used in this analysis come from the following sources. The input assumptions and the secondary energy demand are taken from DOGR (see Appendix B) and the scenario results themselves come directly from the final computer printouts of the IIASA global energy scenarios, available from the IIASA Energy Group. See Appendices B, C, and E for examples of the numerical data.

We begin the analysis by exploring the specific role that the model (MMI) played in calculating the scenarios from the assumptions. For this purpose,

*Some general considerations will be discussed in Section 5 which will help to explain why the models behave as they do.

we will study the relationship between the model outputs (scenarios) and the model inputs (assumptions). The idea is to start with the assumptions and to use them to generate rough *approximations* of the scenarios. Then, by comparing these approximations with the actual scenarios, we should get some idea of the effect of the model's calculations and iterations in producing the scenarios. Thus, in a sense, the input assumptions will be distilled from the model in order to expose the dynamic role of the model itself.

To this end, we start with certain input assumptions and proceed in a heuristic manner, combining them in a simple and obvious way. This will produce a crude zeroth-order scenario which is based purely on selected input assumptions. The criterion for selection will usually be cost minimization, meaning that an unrefined form of optimization is involved. However, no equations will be solved, no dynamics will be simulated, no iteration will be performed, and no significant calculations or consistency checks will be carried out. Instead, a straightforward analysis will be performed by intuitively selecting what seem to be the most important input assumptions and putting them together in a natural way. In most cases, the analysis will simply amount to plotting a few curves on the same graph (where the curves to be plotted are given explicitly in the form of input assumptions to MMI). The resulting scenario will then be compared with the actual scenario that was produced as output from MMI.

Throughout this discussion, the term *scenario* will be understood to denote the published results that were obtained by the IIASA Energy Group from MMI. Meanwhile, for convenience, the simplistic scenario obtained from the input assumptions will be called the *scenariette*. Note that this analysis is not an attempt to design a new or realistic energy model; rather, the aim is to understand the effect that the dynamic calculations and iterations performed by MMI have on the assumptions that are fed into MMI. This will be done by effectively viewing the model's output alongside its inputs; thus the scenariette is a crude sketch compiled from certain *inputs* to MMI, and the scenario is the *output* from MMI.

3.2. Primary Energy

There are four primary energy sources to be considered; oil, coal, natural gas, and uranium. Since oil is a key component of the global energy system, it is a natural starting point. The input data to MMI specify three separate cost categories of this resource, which together define a kind of step function for the cost of oil. Category I is the least expensive, with a unit cost of $62/kWyr,* and includes mainly conventional domestic oil, both existing reserves and those remaining to be discovered. Category II ($103/kWyr) includes some additional undiscovered reserves, as well as some oil from unconventional sources. Category III is the most expensive ($129/kWyr), consisting of oil from unconventional sources such as oil shales, tar sands, offshore and polar oil, and oil obtained using enhanced recovery techniques. These categories and cost assumptions are the same for all world regions, and each particular region is endowed with a given (assumed) amount of oil in each category. For example, region III has 17.48 TWyr of oil in category I, 3.3 TWyr in category II, and 121.36 TWyr in category III. These figures represent the overall amounts of these resources that are sitting in the ground at the beginning of the 50-year time span, available for extraction. Similar cost categories exist for the other primary energy resources.

*This is equivalent to approximately $12.30 per barrel (1975 US dollars). For categories II and III the corresponding figures are $20.40 and $25.60 per barrel, respectively.

Construction of the scenariette for oil

We now use this input structure to sketch a rough portrait of oil supply for region III. Since conventional oil is the least expensive, we use it first. For simplicity, we will assume in the scenariette that the price of this oil will not change as it is depleted, i.e., we assume that the cost of crude oil from domestic reserves remains constant down to the last drop. This is economic sacrilege, but it is acceptable for a rough sketch, and it makes things easy: we simply go ahead and use up all the conventional oil first (category I), and only after it has disappeared do we move on to the more expensive unconventional sources. Thus, in the scenariette, the highly simplistic step function (defined by the input cost data) is adopted as the nonlinear cost function for oil supply.

Since we have decided to use up the cheap oil first, the next question is how long will it last; i.e., how quickly will the oil from category I be consumed? Looking again at the inputs to MMI, we find certain constraints (called maximum resource extraction rates or "production limits" in Figure 2) that limit the rate at which domestic oil can be extracted during each time period. These constraints are supplied to MMI in the form of time series data (meaning that a ceiling on annual extraction is specified for each five-year time period between 1980 and 2030). In the scenariette we extract as much domestic oil as possible (because it is the cheapest source of oil, by assumption). Thus the assumed constraint on domestic oil extraction is simply taken to be the domestic oil production curve in the scenariette. The only thing we have to do is keep a running tab on the cumulative amount of oil extracted — when we pass the 17.48 TWyr mark (mentioned above), we have run out of category I oil (domestic crude), at which time we switch (very abruptly) to category II oil (unconventional); for the high scenariette* this happens between 2020 and

*This refers to the scenariette obtained from the assumptions of the high scenario; the "low scenariette" is analogously defined.

2025 (see Appendix B for details). We then continue in the same fashion: extract oil at the maximum allowable rate until category II oil is exhausted, then switch to category III, and so on.

In addition to domestic oil, there is also imported oil to consider, so we again consult the input assumptions. This time we find a constraint that sets upper limits on the amount of oil that can be imported as a function of time, and this constraint is simply adopted as the curve for imported oil in the scenariette.

This then completes the portrait of primary oil supply, which is displayed in graphical form in Figure 3 (see Appendix B for details). To generate this figure, the individual data points were plotted and then connected by straight line segments to produce curves. Note that the curves are plotted cumulatively to illustrate the composition of crude oil supply and its evolution over the 50-year time horizon from 1980 to 2030. Observe the rather abrupt shift from category I to category II oil that occurs around 2020 – this is due to the oversimplified assumptions made in constructing the scenariette. These sudden changes are even more pronounced in the corresponding scenariettes for region I (Figure D.2 in Appendix D) and in the global oil supply to be discussed later (Figure 13).

Comparison of scenariette with scenario

Now that we have completed this first part of the scenariette, it is interesting to compare it with the results from the published IIASA scenario itself. To do this, we start with a duplicate of the graph in Figure 3, onto which the final scenario results are superimposed by plotting individual data points (which come directly from the MMI computer output listings – see Appendix B). The result of this superposition is shown in Figure 4. Thus Figure 4 is

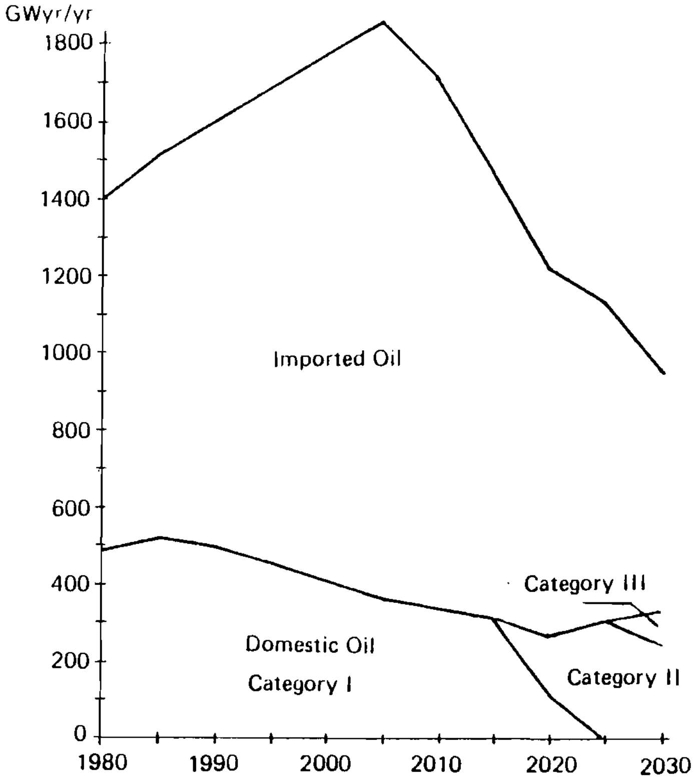

FIGURE 3 Scenariette for crude oil supply (region III high). The curves displayed here are obtained directly from the exogenous input assumptions to the IIASA energy models.

identical to Figure 3 except that some data points have been added; these points are the final scenario results, which are plotted using four different shapes (circles, triangles, squares, and crosses) to distinguish four distinct sets of outputs from MMI. It is important to understand the format of Figure 4, because it is used throughout this section for comparing scenariette and scenario results. The main thing to remember is that the curves display the scenariette (inputs), and the points display the scenario (output).

In Figure 4 we see something quite surprising. The data points from the scenario fall almost exactly onto the scenariette curves. There are some minor differences for imports, but these are insignificant.

A brief review is called for at this point. We started with a handful of input assumptions to MMI; these were used to put together a rough sketch of the crude oil supply in region III. In doing so we made some unrealistic assumptions, while at the same time ignoring various considerations such as

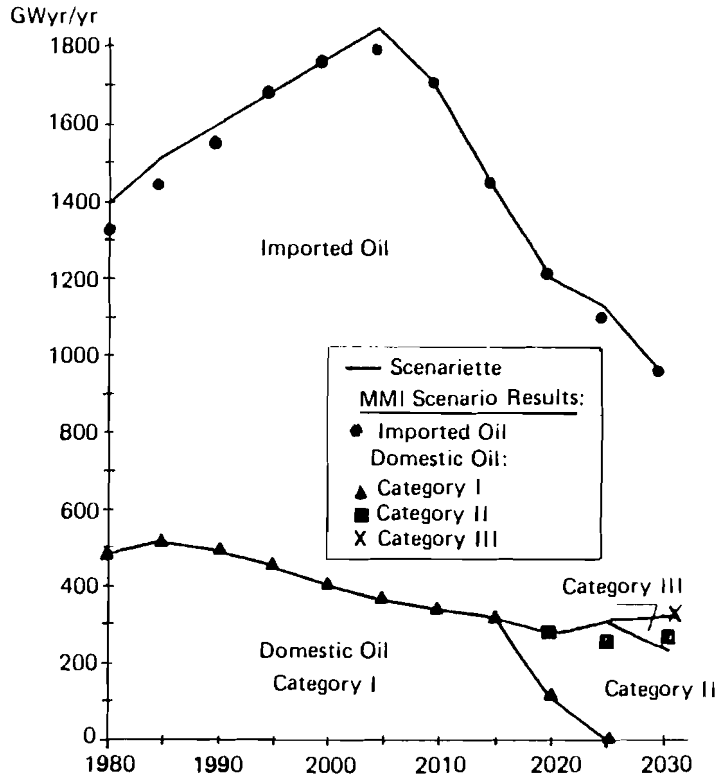

FIGURE 4 Comparison of scenariette with the IIASA scenario results for crude oil supply (region III high, cf. EIFW Figure 17-11E, p. 560). This figure is identical to Figure 3, with the addition of the data points, which are the final outputs from the IIASA energy models. Note the agreement between scenariette and scenario.

price elasticities, consistency, relationships with other sectors of the energy system, etc. The most that was expected from this was a rough qualitative correspondence with the scenario dynamics, and yet somehow the scenariette developed here agrees almost perfectly with the scenario itself, which is supposed to be the product of a careful, detailed, iterative self-consistent optimization procedure. But perhaps this is just an anomaly that holds only in this one particular case. To find out, it is necessary to investigate some further cases.

Scenariettes for other energy resources

The development of similar scenariettes for natural gas, coal, and uranium* produces the curves shown in Figures 5, 6, and 7 respectively (see

*The uranium scenariette is obtained in a somewhat different fashion from the other primary energy scenariettes; see Appendix E.

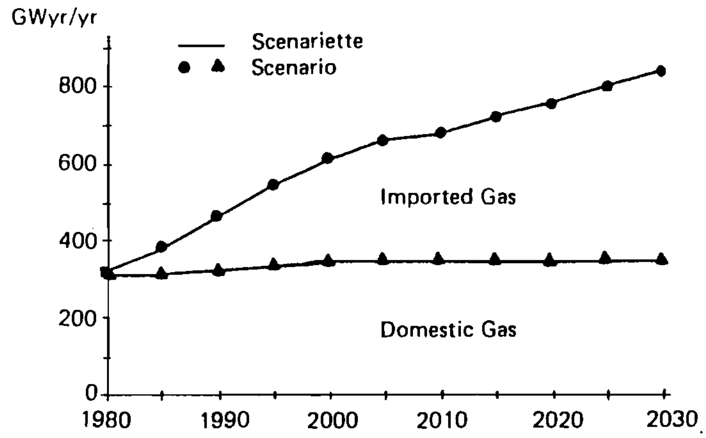

FIGURE 5 Comparison of scenariette and scenario results for natural gas supply — region III high (cf. EIFW, Figure 17-12E, p.568). The curves are inputs to MMI, the points are outputs from MMI.

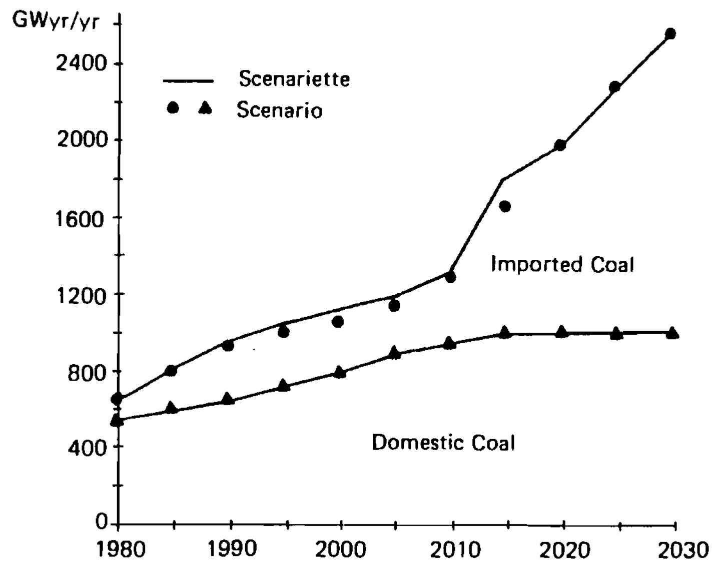

FIGURE 6 Comparison of scenariette and scenario results for coal supply — region III high (cf. EIFW, Figure 17-14E, p.572). The curves are inputs to MMI, the points are outputs from MMI.

Appendix B).

Again, for comparison, the scenario results are shown as data points, and once again the agreement is essentially perfect. No analysis of any kind was

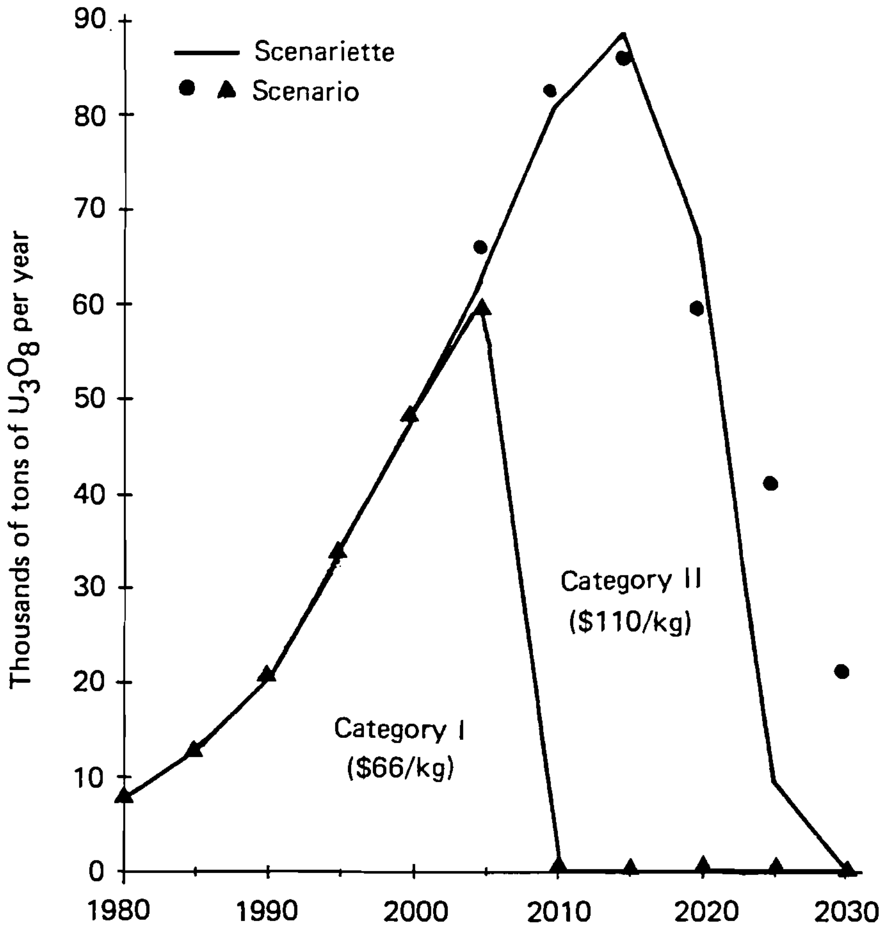

FIGURE 7 Comparison of scenariette and scenario results for natural uranium extraction — region III high.

involved in generating Figures 5 and 6; the curves are plotted directly from the exogenous *input* listings to MMI, and the points are plotted directly from the *output* listings from MMI (see Appendix B). In some ways these plots look deceptively trivial, which obscures their importance. It is crucial to understand that they are not the result of some curve-fitting exercise. Rather, the data points are the outputs from MMI, and the solid curves are the input assumptions to MMI. The fact that they agree perfectly means that, in effect, the scenario results are prescribed exogenously in the input assumptions, and the model itself just reproduces these assumptions.

Perhaps these findings are not so surprising if we consider that we have looked only at the high scenario. It is quite possible that the entire energy system is operating at maximum capacity in the high scenario, straining every bolt as it were, so that the system comes right up against the constraints. If so, then it is important to look also at the low scenario, where the strain on the system should be eased considerably. This is done in Appendix B, and again, essentially perfect agreement is observed between inputs and outputs in almost all cases.

This concludes the discussion of primary energy. The principal finding is that both stocks and flows of primary energy sources in the IIASA scenarios are effectively prescribed in the form of exogenous assumptions and constraints. In the schematic diagram of MMI in Figure 2, most of these assumptions are contained in the oval labeled P (for primary). Note that this oval lies entirely outside the iterative model loop, and that there are no "major feedbacks" into this oval, indicating that these assumptions are not subject to modification. In fact, the model essentially performs the same analysis presented above in developing the scenariette.

3.3. Secondary Energy

As discussed earlier, a principal objective of MMI is to describe an energy supply system that fulfills the demand at the lowest cost. Therefore we shall begin the analysis of the secondary energy system by considering the cost assumptions for various secondary energy supply technologies. These are given in Table 1, which is reproduced from Table 17-4 in EIFW (p.527). The capital and variable costs have the constant values shown, for all regions and all time periods. Furthermore, these costs are identical in both the high and low scenarios, even though these scenarios are intended to "span a sufficiently wide range in order to incorporate the unavoidable uncertainties" (EIFW

p. 425). The assumption of fixed costs is one of the main reasons for the high degree of structural uniformity exhibited in the high and low scenarios for all seven world regions. The final product costs increase in some cases from the values shown after the cheapest category of the corresponding fuel is exhausted. Although these variations in cost are minor, they are responsible for some curious behavior to be discussed in Section 4. For now, we present two secondary supply scenariettes; one for electricity and one for liquid fuels.

TABLE 1 Cost assumptions for major competing energy supply and conversion technologies (reproduced from EIFW, p.527, Table 17-4).

	Capital Cost (1975$/kW)	*Variable Cost (1975$/kWyr)*	*Final Product Cost (1975$/kWyr)*
Electricity Generation			
Coal with scrubber	550	23	154
Conventional nuclear reactor (e.g., LWR)	700	50	136
Advanced reactor (e.g., FBR)	920	50	143
Coal, fluidized bed	480	36	152
Hydroelectric	620	8.5	85
Oil fired	350	19	256
Gas fired	325	16	216
Gas turbine	170	17	241
Solar central station	1900	28-60	297
Synthetic Fuels			
Crude oil refinery	50	3.7	75
Coal gasification ("high Btu")	480	40	125
Coal liquefaction	480	40	125

As mentioned above, the demand projections for secondary energy in these scenariettes are taken from the endogenous "Secondary Fuel Mix and Substitutions" procedure, labeled D (for demand) in Figure 2. Thus the present analysis treats these projections as given, and focuses on the supply side of the scenarios.

Scenariette for electricity generation

Given the objective of cost minimization, we start by looking at the relative cost assumptions for electricity generation. In the last column of Table 1, hydroelectric power is found to be the least expensive technology, at $85 per kWyr. Following this, the next cheapest is nuclear power, running from $136 for LWR to $143 for FBR, then comes coal-fired power at $152 to $154,* and the remaining electricity sources become increasingly more expensive. Thus we start with the cheapest source (hydro), take as much as possible, then move on to the next cheapest source (LWR), again taking as much as possible; and continue in this fashion until the demand is met. Thus, to build the scenariette, the technologies are chosen in the order of their cost, and each one contributes an amount equal to its supply constraint. This guarantees that when we reach the demand level, we have specified the least expensive supply mix that meets it.

This procedure for developing the electricity scenariettes is described in more detail in Appendix C. The end result is a scenariette consisting of an assemblage of constraints, stacked one on top of the other, defining the evolution of the electricity supply system. These constraints, which are called "maximum build-up rates" in Figure 2, form another group of assumptions supplied to MMI. In most cases they are derived from the following difference equation (EIFW p.530)

$$y_t = \gamma \, y_{t-1} + g \qquad (1)$$

where y_t represents the annual addition to the capacity of a particular technology during the time period t, γ is a constant growth parameter, and g is an initial condition that starts the process off at the "start-up" time, t_0. As will be

*Since these cost about the same and are both coal burning technologies, no distinction is made in the scenariette. It so happens that this distinction was unimportant in the scenario as well.

seen shortly, this very simple equation, which produces exponential growth,* is by far the most important factor in determining the dynamics of the secondary supply mix. The parameters γ, g, and t_0 have one fixed set of values for all the developed regions (I, II, III), and a fixed but different set of values for the rest of the world (regions IV through VII).

Figure 8 displays the scenariette for electricity supply in region III. The area labeled "coal & other" in this figure is due almost entirely to coal. "Other" refers to a thin sliver (due to current oil- and gas-fired power plants) which disappears by 2010, and a barely discernible contribution from solar energy after 2020. The demand projection is shown in Figure 8 by a dashed line.† Since the demand is taken as given, a dashed curve is used to distinguish it from the solid curves, which are the results of the scenariette.

Comparison of scenariette with scenario

Turning now to Figure 9, we find that the MMI scenario is identical to the scenariette up through 2010. Notice that after 2015, the data points for LWR and FBR seem to be deflected away from the demand projection as they approach it. During these final 15 years of the time horizon, coal is being phased out very rapidly, resulting in extensive underutilization of coal-fired capacity. However, MMI imposes an economic penalty for excessive underutilization, so that the rapid decline of coal is attenuated somewhat, producing the observed deflection. This same effect occurs to a lesser extent within the nuclear contribution itself, as LWR gives way to FBR.

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*Denoting the start-up time by t_0, the initial condition is $y_{t_0} = g$. With this condition, Equation (1) has the unique solution

$$y_t = g\,[\gamma^{(t - t_0 + 1)} - 1]/(\gamma - 1) \text{ for } t \geq t_0 \ ,$$

which is exponential in t. The numerical values for γ exceed unity in all cases (see DOGR).

†It is interesting to note in passing that this demand projection entails a 2.7 fold increase in electricity consumption per person living in region III by 2030.

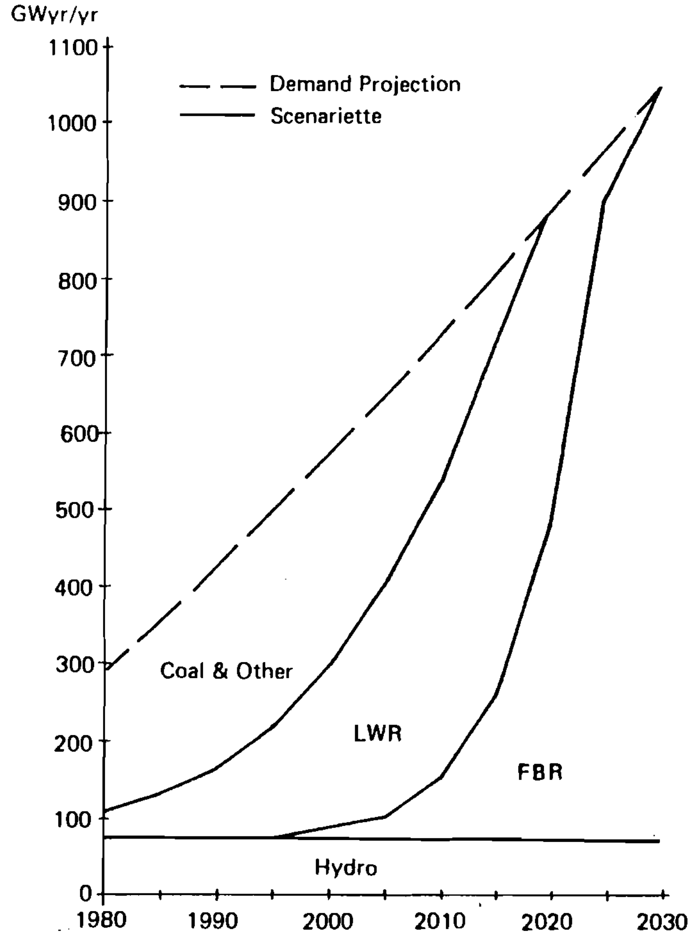


FIGURE 8 Scenariette for electricity generation — region III high. The solid curves are obtained directly from the exogenous input assumptions to the IIASA energy models. The dashed curve is the endogenous demand projection.

Notice that MMI has no knowledge of the physical significance assigned to the particular results that it produces. For example, it might be tempting to conclude from Figure 9 that the fast breeder reactor (FBR) will dominate the future electricity supply. However, this is an assumption supplied *to* the model, and not really a result or conclusion derived *from* the model. The curve labeled "FBR" in Figure 9 is the immediate consequence of three parameter values [γ, g, t_0 in Equation (1)] supplied directly to MMI by the user which reflect his or her ideas about the future role of FBR in the electricity supply. But the model itself knows nothing about the physical interpretation attached to the resulting curve, nor can it in any way assess the feasibility, desirability, or implications of such an option. It simply displays the curves

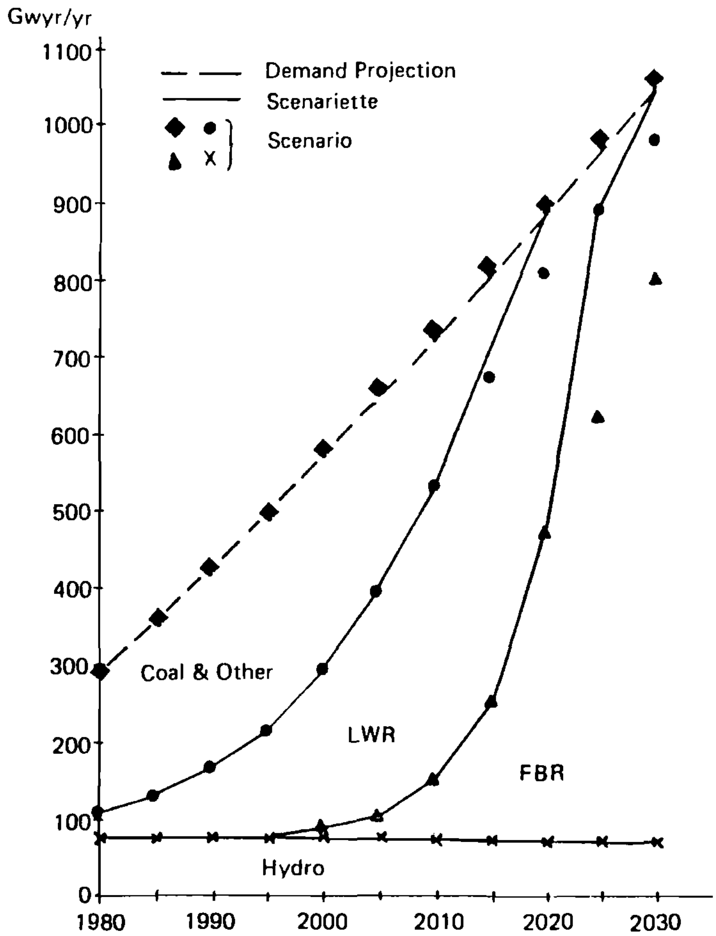


FIGURE 9 Comparison of scenariette and scenario results for electricity generation — region III high. This figure is identical to Figure 8, with the addition of the data points, which are the outputs from the IIASA energy models. Note the close agreement.

that result from the user's inputs, and as such, it serves as a framework for displaying whatever free-hand sketches the user dreams up.

It might still be tempting to imagine that the low scenario will not behave quite so predictably, since the energy system is under considerably less strain in this case, but Figure 10 reveals that this is not the case. Once again, the scenario coincides with the scenariette for 35 years before the model exerts its influence.

Scenariette for liquid fuel supply

The analysis for the supply of liquid fuels is essentially the same as for electricity, so only the results are presented here (see Appendix C for details).

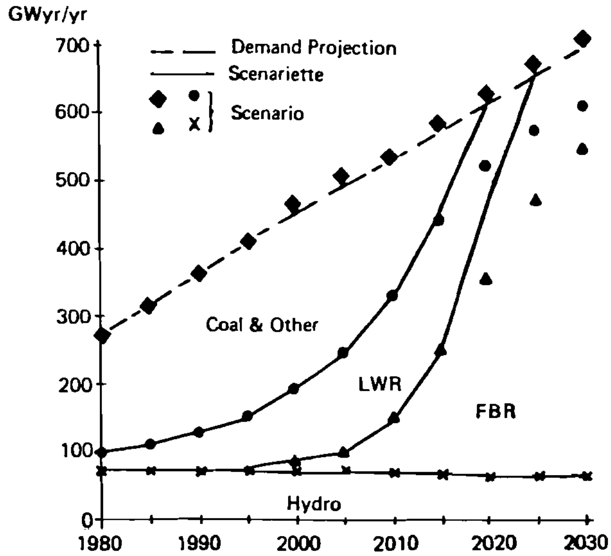


FIGURE 10 Comparison of scenariette and scenario results for electricity generation — region III low.

Figures 11 and 12 show the high and low scenariettes for liquid fuel supply, respectively, in region III. The scenario results are superimposed in the usual way, and they exhibit close agreement.

3.4. Scenariettes for Other Regions

So far we have looked only at results for region III, which includes some of the most developed and energy-intensive nations in the world. It is interesting to consider the opposite extreme, and therefore several results are presented in Appendix D for region V (South and Southeast Asia and most of sub-Saharan Africa), which is the least "developed" and most populated of the seven world regions. In addition, key results are included for region I (USA and Canada), which look very much like those for region III. A cursory look at the remaining regions indicates that the scenariette and scenario results generally agree very well, but these cases have not been analyzed in full detail.

Perhaps the most critical aspect of the global energy system is the supply and international trade of oil. Figure 13 shows the high scenario and corresponding scenariette for the global free-market oil supply (excluding the centrally planned economies of regions II and VII). As shown in Appendix B,

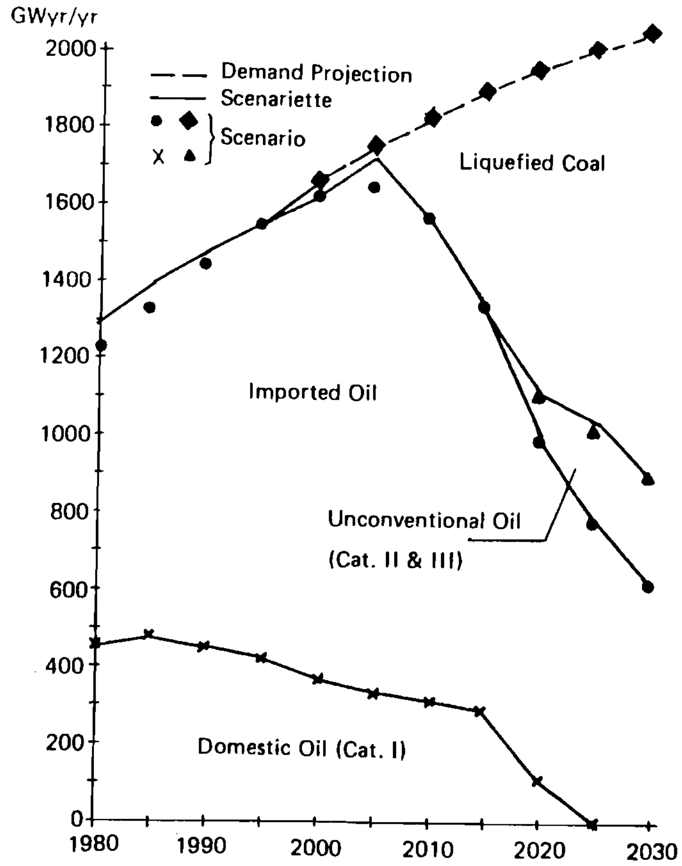


FIGURE 11 Comparison of scenariette and scenario results for liquid fuel supply — region III high (cf. Figure 17-11E, EIFW, p.560).

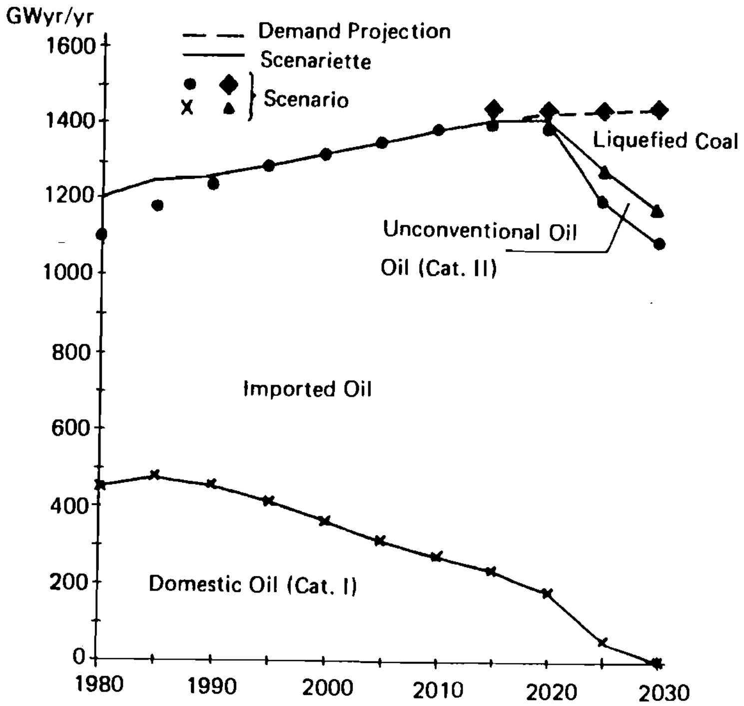


FIGURE 12 Comparison of scenariette and scenario results for liquid fuel supply — region III low (cf. Figure 17-11F, EIFW, p.560).

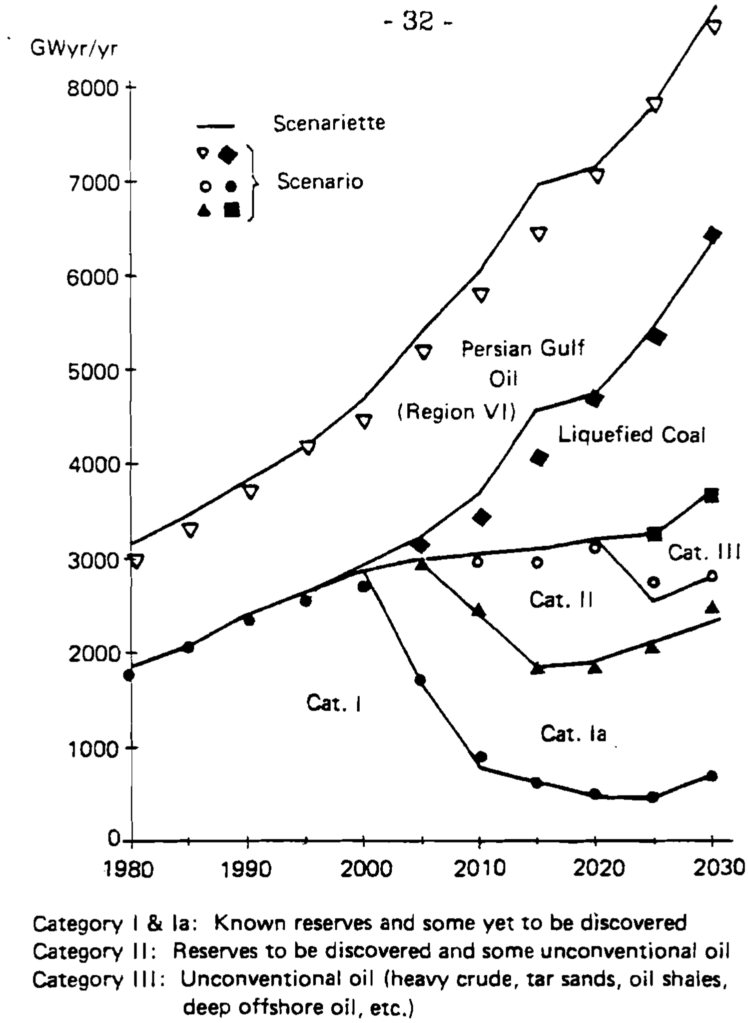


FIGURE 13 Comparison of scenariette and high scenario results for world oil supply (excluding centrally planned economies; cf. *Science* article (Häfele, 1980a), and EIFW, Figure 20-1, p.662, and Figure 25-9, p.798).

this scenariette was generated by aggregating a few input assumptions (contained in the two ovals labeled P and S in Figure 2) which are exogenous to the model. A variant of Figure 13 has been published* in *Science* (Häfele, 1980a) and *Scientific American* (Sassin, 1980), as well as the *Executive Summary* (McDonald, 1981), and twice in EIFW (p.662 and p.789) -- clearly these results are offered as a key finding from the IIASA energy study. As displayed in Figure 13, the differences between scenario and scenariette are slight, revealing that these important results were essentially exogenous assumptions. This

*The published figure is somewhat different from Figure 13, in part because it probably includes "constraints for the gradual buildup and depletion of separate oil categories." (EIFW, p.558) This brief reference (which occurs in the caption of another figure) is the only mention of these constraints – they are not part of the model, and I have not found them documented anywhere. In addition, the published figure incorporates specific dynamic estimates of quantities of oil remaining to be discovered, which are also undocumented.

figure is presented in *Science* as evidence for the need to exploit unconventional oil and coal liquefaction.

3.5. Conclusions

The basic conclusion of this section is that the dynamic and analytic contents of the IIASA energy supply scenarios are directly attributable to assumptions and quantitative judgments that are specified outside of the set of mathematical models. In some cases, the models are found to reproduce the input assumptions precisely; in others, they introduce unimportant perturbations to the input structure. At best, the models themselves perform a highly simplistic analysis that is essentially the same as the back-of-the-envelope calculations presented above (and described in full in Appendices B and C).

In view of these findings, a natural question to ask is: where do the various quantitative assumptions and judgments that are responsible for the scenarios come from? Only brief descriptions of these assumptions are given in EIFW (which is described as the full technical report from the study). Almost no empirical evidence or theoretical justification is included to substantiate the assumptions, and no quantitative details are included to indicate how these numbers were obtained. Instead, they are candidly referred to as "guesstimates" (EIFW, p. 531), "rough average (sometimes consensus) estimates" (p. 528), "best available assessments" (p. 581), etc. Thus whatever analysis was carried out to arrive at these numbers is undocumented and inaccessible: "these data, while arrived at by averaging many sources, are still highly judgmental" (p. 527). Since the scenarios are largely copies of these assumptions, the conclusion that begins to emerge is that the scenarios are closer to considered opinion than objective analysis. We shall return to this point later (Section 6), after exploring the robustness of the scenarios.

4. ROBUSTNESS OF THE IIASA ENERGY MODELS

> ... All of this leads to a belief (or hope) that the scenarios here are robust, that they can stand up against events whose impacts, in human terms, may be large.
>
> — *Energy in a Finite World*, Vol. 2, p.395

It is clear that "in practice, of course, all the assumptions are very rarely satisfied." This statement comes from Pearson's *Handbook of Applied Mathematics* (1974) which reads further: "Robustness is a semimathematical concept. A procedure is robust if it still works 'fairly well' when the assumptions are 'not quite' satisfied." Thus robustness is the property that an analysis must have if it is expected to be of some validity in the face of uncertainties in the underlying assumptions. To establish robustness, the standard procedure is to perform a detailed analysis of the sensitivity of the quantitative results with respect to variations in the assumed input data. In the case of the IIASA energy scenarios, it has been asserted that "the sensitivity analysis was done — at length" (Rogner 1983).

In this section, we explore the sensitivity of the scenarios with respect to certain assumed input data. This sensitivity analysis focuses on the energy supply model MESSAGE, because "the assumptions and results [from MESSAGE]... represent, in some ways, the core of the energy studies reported in this book" (EIFW, p. 402). The major finding is that the supply scenarios are not robust with respect to variations in several different input data. One example concerns the structure of the nuclear contribution, which is found to be sensitive to minor variations in the assumptions concerning availability and cost of uranium. Another example shows that the supply scenarios are unstable with respect to minor variations in cost assumptions for technologies. Finally, the documented sensitivity analysis is reviewed, and it is found to be seriously lacking in standard sensitivity tests.

4.1. Sensitivity to Estimates of Inexpensive Uranium

Recall from the previous section that a key factor in determining the electricity supply mix is the hierarchy of production costs. The evolution of these costs is presented in Figure 14, from which we see that most costs are assumed to remain constant (in real terms) for the next 50 years.* Even though this is a highly unlikely proposition that explicitly presumes perfect information about the future, it can be justifiably dismissed as immaterial *if* the outputs from the model are found to be insensitive to it. In fact, as explained in EIFW, "The desire for data robustness dictated our decision to avoid an approach relying completely on prices" (p.27), from which it is to be expected that the scenarios are insensitive to variations in the assumed cost projections shown in Figure 14. This will be investigated shortly. For now, observe that the curve for light water reactors (LWR) exhibits a small instantaneous jump, or step, in the year 2005 (see Figure 14). This is due to an abrupt increase in the cost of uranium (from \$66 to \$110 per kg U_3O_8) which is the result of a shift in resource cost category, as discussed in Section 3 (see Figure 7). This increased fuel cost raises the cost of electricity generated from LWR by \$10 per kWyr (from \$136 to \$146 – see Appendix E), as illustrated by the step. Such a minor increase (7%) is unimportant in itself, but notice something else in the figure. It happens that the fast breeder reactor (FBR) becomes an available option in the year 2000 (just before the step), at a cost of \$143 per kWyr of electricity generated (see Table 1). At this time, LWR is still the favored technology (costing \$7 less per kWyr) but then, just five years later, the step occurs (causing LWR to go up by \$10 to \$146) and suddenly FBR

*These are sometimes called static costs because they do incorporate the discount rate and other dynamic factors. However, most of these factors do not affect the ***relative*** cost structure, which is of interest here. See Appendix E and Schrattenholzer (1981, p.17) for more details.

becomes the favored technology because it is $3 cheaper. Thus the step serves to boost the cost of LWR by just enough to give FBR a slender (2.10%) cost advantage (which holds from 2005 onwards). The result is that FBR is built up as rapidly as possible, while LWR is phased out (see Figures 9 and 10). If the step were not there, the model would still eventually introduce FBR in this particular case (region III), but not until much later when uranium becomes scarce.*

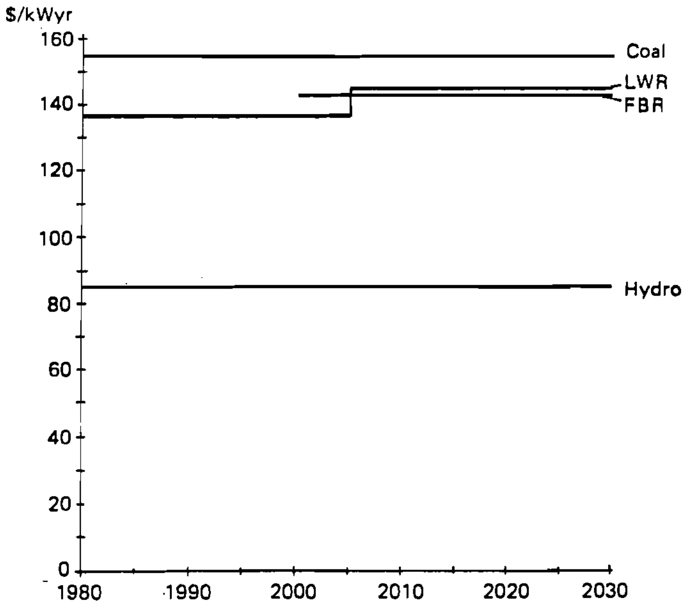


FIGURE 14 Assumed cost projections for electricity generation in IIASA scenarios; constant 1975 US dollars (this figure is for region III high).

It is obvious that a three-dollar economic advantage that is a consequence of a 7% cost jump that is caused by a resource cost increase of 70% that is slated to occur instantaneously 25 years from now is merely an artifact of the model, rather than a realistic expectation. Nevertheless, this feature of the model is the major factor determining the introduction time for the FBR in

*Note that the delicate cost structure in Figure 14 can be upset by an increase of 2.5% in the assumed cost of FBR or a similar decrease in the cost of LWR.

the scenarios. The electricity generation cost assumptions for all other scenarios are identical to those shown in Figure 14, the only differences being in the time at which the "LWR-step" occurs. This is governed by the quantity of cheap uranium available, which is an uncertain exogenous constraint supplied to the model. The effect is manifested in the following mechanism: by specifying the constraint on the availability of cheap uranium (which is itself quite arbitrary), the analyst is also controlling the time at which FBR becomes the favored technology. For example, in region IV (Latin America), the fraction of the assumed total available uranium that is assigned to the cheaper cost category is just 1.6%. This results in LWR-steps occurring in the year 2000 for the high scenario and 2005 for the low scenario (which coincides with the first availability of FBR on a commercial scale). However, by slowly increasing the fraction of uranium allocated to the cheaper category, these steps are moved forward rapidly in time, thereby greatly delaying the introduction of FBR. In the low scenario, for example, a simple calculation (Appendix E) shows that if the quantity of cheap uranium is increased to just 8.7% of the total, the LWR-step is pushed more than 25 years into the future, beyond 2030. The result is that the entire nuclear contribution is filled by LWR alone, and FBR is never introduced at all (see Appendix E).

In some cases, the step in the LWR curve never actually occurs. In the low scenario for region V, for example, there is still plenty of cheap uranium left in 2030. Nevertheless, FBR is still introduced in this case, starting in 2005, and its contribution expands at the maximum permissible rate thereafter. This occurs despite the fact that the entire contribution from FBR could be supplied at a lower cost with additional LWR capacity (within the framework and constraints of the model; see Appendix E). Thus, given the least-cost objective of MMI, it is curious that FBR plays a significant role in this scenario. A close scrutiny of the computer input files reveals undocumented cost reductions for coal-fired power during the first 25 years of the time horizon. This has the effect of preventing a full buildup of LWR, which in turn is apparently the reason that FBR is introduced at the maximum rate in this scenario (see Appendix E for details, and a related example for region VI).

4.2. Sensitivity with Respect to Relative Cost Structure

In order to ensure robustness (as well as realism), it is necessary to explore the sensitivity of the scenarios with respect to assumptions that are known to be unrealistic or unlikely, such as the constant cost projections displayed in Figure 14. The importance of this is underscored by the observation that already by 1982, the real-world costs of generating electricity from both coal-fired and nuclear power had more than doubled (in real terms) from the values shown in Figure 14 (IAEA, 1982). However, although this has had its effect on energy investments and the world economy as a whole, what is much more crucial for the energy sector is the possibility of changes in the *relative* costs of different energy supply technologies.

Such relative cost changes have indeed been occurring in the real world. A recent review of nuclear power costs around the globe concludes that "nuclear plant investment costs are rising more rapidly than the costs for coal-fired plants, with the possible exception of Canada and France" (IAEA, 1982). In the USA, for example, the gap between future nuclear and coal-fired costs of electricity generation has disappeared, and the cost of nuclear power exceeds that of coal-fired power in some parts of the country (EIA, 1982). Thus, it is of particular interest to consider region I (USA and Canada) in performing a sample test of the sensitivity of the IIASA scenarios to changes in the relative cost structure.

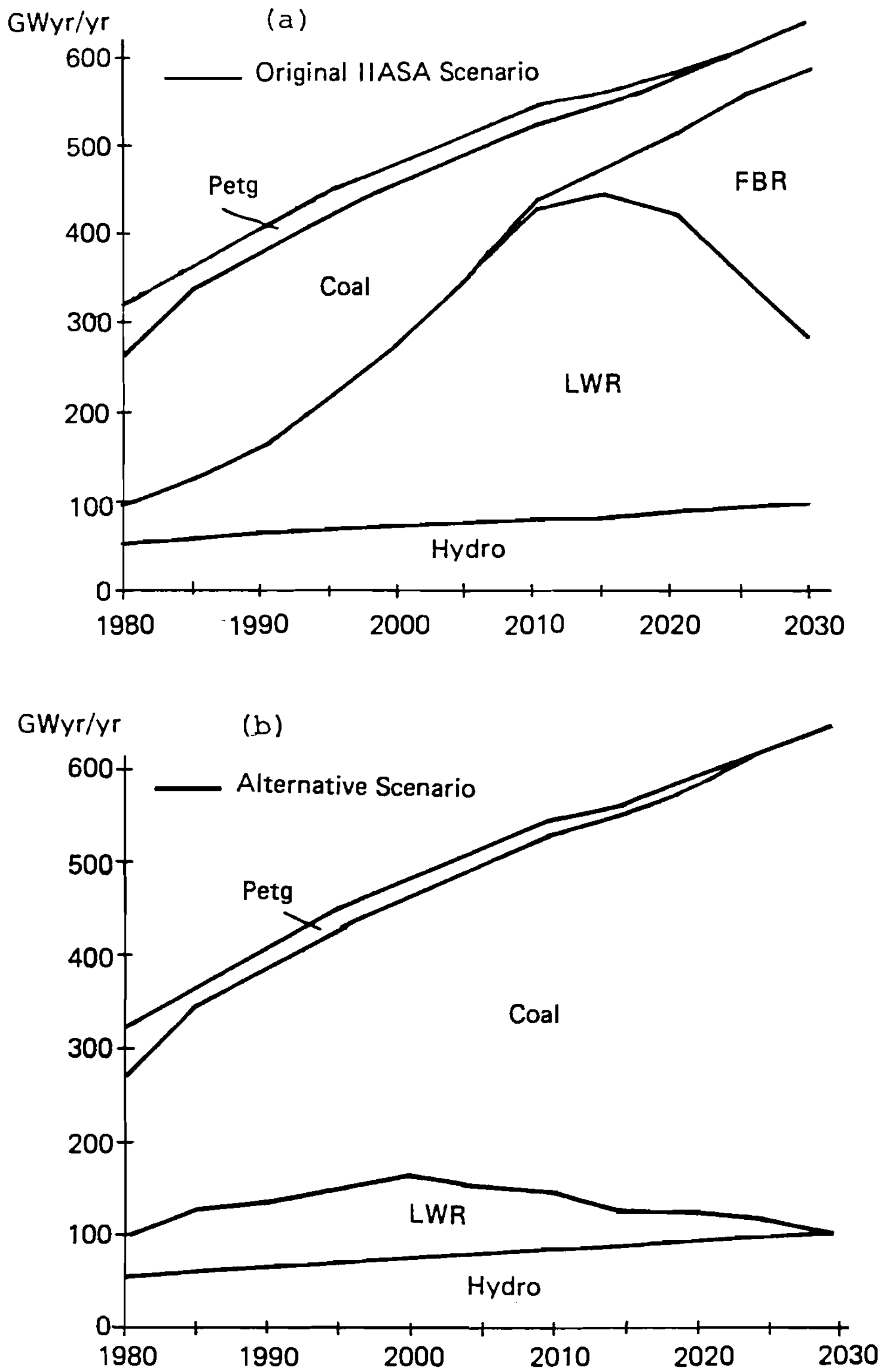


FIGURE 15 Sensitivity to cost assumptions in IIASA scenario for USA and Canada (region I low). (a) original scenario results for electricity generation; (b) new scenario results, assuming that nuclear costs are increased 16% and that the coal extraction limit is raised 7%.

The results of this sensitivity test are summarized in Figure 15. Part (a) of the figure displays the electricity supply system of the IIASA low scenario for region I (note that this figure shows the actual scenario results, and not a scenariette). Now suppose the cost of nuclear power is increased by 16%.* As revealed by a straightforward calculation (Appendix E), this produces the greatly altered scenario shown in Figure 15(b)†. In this new scenario, coal-fired power accounts for most of the electricity production, while LWR is phased out over the 50-year time horizon, and FBR is never introduced at all. By 2030, the coal contribution to electricity supply reaches 85% (compared with 8% in the original IIASA scenario in Figure 15(a)), and the nuclear contribution disappears entirely (compared with 77% in the original scenario). However, the main point here is not what actually happens under different cost assumptions, but rather that small changes in these assumptions can produce tremendously different outcomes from the model.

4.3. Documentation of Sensitivity Analysis

In view of the above findings, it is of interest to look at what is reported in the documentation concerning sensitivity analysis. In EIFW there is a chapter (18) entitled "Alternatives and Sensitivities", most of which is taken up with descriptions of three alternative cases (including a nuclear moratorium scenario, an enhanced nuclear scenario, and a reduced demand scenario). These alternatives are considered extreme departures from the standard high and low scenarios, and therefore they are naturally not developed or

*Such an increase can easily be envisaged in *any* of the IIASA world regions, for a variety of reasons. For example, the costs of decommissioning nuclear power stations (which could be considerable) are not included in the IIASA cost assumptions. Other factors that could increase the cost are stricter safety regulations, new requirements for waste treatment, tighter emission control standards, legal entanglements, construction delays, etc.

†In order for this new scenario to be feasible, it is necessary to increase the assumed ceiling on coal extraction in the scenario by 7%. See Appendix E.

documented in great detail. In addition, they are not used as a basis for drawing quantitative conclusions about the world's energy future. In some sense, these alternative scenarios may be viewed as a non-standard form of sensitivity analysis, since they involved the modification of various assumptions.

The robust conclusions and policy recommendations from the IIASA study are based on the high and low scenarios themselves; thus it is particularly important to explore sensitivity in these scenarios. For this purpose, the final section of the chapter (pp. 613–620) presents "some sample 'sensitivity' analyses ... [which] probe variations in results following extreme variations in assumptions" (EIFW, p. 594). Most of this section is taken up with general discussions about the effects of an altered oil production ceiling (in region VI), and the possible effects of technological breakthroughs, concluding with a short subsection entitled "Escalation in Energy Costs" (pp. 618–20). This opens with a general discussion of the effects of tripling the cost of synfuels, and then treats "the more constructive consideration ... of the possible variations among the relative price changes of new sources of energy" (EIFW, p.619). Three specific possibilities are considered:

(1) doubling all electricity generation costs

(2) doubling the costs of fossil fuels

(3) both of the above

These possibilities are found to result in corresponding demand reductions of 8, 18, and 24%.*

*These calculations are based on implicit price elasticities which are calculated independently of the model in an earlier chapter (EIFW, Chapter 15).

Given the sensitivity that was observed earlier in the electricity supply scenarios, case (1) is of particular interest. For this case, the demand for electricity is calculated to drop by just 8%, which suggests robustness. However, note that in the analysis, the electricity generation costs are all uniformly doubled, which preserves the relative structure that is responsible for the unstable behavior in the scenarios. By doubling the costs, each curve in Figure 14 is shifted vertically upwards but the *relative* positions of the curves are precisely maintained. Hence, the sensitivity to variations in the relative cost structure remains unexplored in this analysis.

No further sensitivity tests are presented for the scenarios, and no references are included to indicate where such analyses might be found. A search through DOGR and the many research reports turned up one brief mention of the need for sensitivity analysis, directing the reader to EIFW.

In 1974, two IIASA research memoranda were published (see Appendix F) which presented several sensitivity analyses of the earliest prototype of MESSAGE (developed by Häfele and Manne 1974). A number of sensitivity problems were revealed, leading to the conclusion that "more work is needed in several directions" (Konno and Srinivasan, 1974).* In 1975, an IIASA research report was published which described an extension of the prototype model and included several sensitivity tests with respect to variations in the cost assumptions for technologies and resources. It was found that the contributions to total energy supply from a given technology could range from 0% to over 70% as the capital costs or fuel costs were varied (see Appendix F). These findings are not cited or investigated further in the later documentation.

*Neither of these papers is explicitly referenced in any of the later documentation. They do appear in a list of related IIASA publications (EIFW, p. 422)

4.4. Conclusions

It has been found in this section that the IIASA energy supply scenarios are highly sensitive to arbitrarily prescribed input data, which are known to be uncertain. One example of these difficulties involves the contribution from the fast breeder reactor (FBR) in the scenarios. Both the time at which the FBR is introduced and its subsequent rapid expansion are strongly dependent on a 2% cost advantage that is the result of a small, artificial step in the cost projection for LWR. The temporal location of this step is in turn very sensitive to uncertain estimates of available uranium resources and their costs.

Another difficulty concerns the magnitudes of the contributions from the various supply options, which are based on fixed relative cost assumptions that are presumed to hold for the next 50 years. It is found that small changes in the assumptions about relative costs and resource availability can cause the model to produce radically different supply scenarios. This finding is consistent with early studies (for a prototype model) that showed tremendous sensitivity with respect to variations in the cost assumptions for technologies and resources. Given the large uncertainties in the future costs of energy resources and supply technologies, this demonstrates the futility of using simple cost minimization LP models for describing robust supply scenarios over a long time horizon.

Finally, as explained in EIFW, although the assumed costs "will surely change over time, perhaps dramatically, just one cost estimate for each technology is used here for the entire planning horizon. Sensitivity analyses can test alternative cost estimates." (EIFW, p. 527). However, the documented sensitivity analysis includes only one such test, and this particular test obscures the critical sensitivity to variations in the relative cost structure. In addition, early work on sensitivity analysis is not cited. Finally, regarding "the availability of natural uranium, "there is a far greater lack of basic information than in the case of fossil fuels" (Häfele, 1983a). Nevertheless, there are no sensitivity tests with respect to the assumed costs and availability of uranium.

The major finding of this section is that the IIASA energy supply scenarios are seriously lacking in robustness, particularly with regard to the contribution from nuclear power. This lack of robustness precludes the possibility of drawing reliable conclusions from the scenarios about future energy supply strategies.

5. DISCUSSION OF THE MODELS

This section provides a brief discussion of the models, and offers a few possible reasons for the findings presented above. We begin by discussing the iterative process in MMI, followed by a discussion of the linear programming model, MESSAGE.

5.1. Iteration in MMI

The process of iteration has tremendous "science appeal" because it implies that an objective rationale escorts an initial guessed solution through the haze of the unknown, correcting inconsistencies, and reducing errors to eventually produce a correct, self-consistent solution to the problem at hand. Indeed, Newton's method in numerical analysis and the Hartree-Fock self-consistent field method in quantum mechanics are brilliant examples of this. Against this background, it is perhaps natural to expect that the iteration in MMI would entail corrections and adjustments of key physical and economic variables, and their interrelationships. However, the description of MMI given in Section 2 presents the models and their iteration in the best possible light. There are a number of caveats and serious inconsistencies which appear throughout the documentation. The most important of these is that the feedback link from IMPACT to MEDEE-2 exists only "in theory" (EIFW, p.404), which means that the economic variables were not incorporated into the iteration process (see Figure 2). Indeed, the IMPACT model itself was an unreliable component of the entire modeling exercise, as revealed by the following description (Häfele 1981b):

> Energy investments were analyzed using an input/output procedure, despite the difficulty of providing all the coefficients even for today's conditions, as there is practically no other useful method. For this reason, we refrained from relying on this procedure rigorously as an overall procedure. ... to have relied heavily on this approach would

> have amounted to a way of concealing our ignorance. The input/output procedure for determining energy investments was therefore applied reluctantly and *only at a place where no major numerical conclusions for further modeling steps would be drawn from it.* [emphasis added]

Thus the iterated model loop consisted of just MEDEE-2 and MESSAGE (see Figure 1), while IMPACT served as a "monitoring model" (Rogner, 1983). This means that no *full loop* pass was made through the three-model loop, contrary to certain statements in the documentation (see Wynne, 1983, for further discussion). More importantly, it means that constraints on capital investments, land, labor, equipment, water, and materials were not explicitly accounted for in the models, which seriously diminishes the credibility of the scenarios, particularly because of their capital-intensive supply strategies.

In EIFW, two specific examples of the iterations that were performed with MEDEE-2 and MESSAGE are described (pp. 404-7), both for region III. The first one involved an increase in the share of natural gas in the heating sector from 60% (of the fossil fuels used for heating) to 70% by 2030. The second involved a decrease in the assumed rate of penetration of electricity into the heating market, which resulted in a decrease in electricity consumption of 12% by 2030.

Detailed considerations such as these (resulting in 10–15% changes in 50 years' time) were the principal focus of the iteration in MMI, while most of the important economic and physical variables were held fixed or prescribed by assumption. In the previous two sections, a number of input variables were found to be crucial factors in determining the dynamics and supply mix of energy systems in the scenarios. Nevertheless, most of these variables were not included in the iterative process. A good example is the cost of Mid-East oil, which was held fixed for 40 years in all scenarios (DOGR, pp. 14,38,61). Other examples are the resource ceilings and extraction rates, the buildup rates for technologies, and the costs of resources and technologies. As shown in Figure 2, these variables were exogenous to the iterative process in MMI, and were not subject to modification via "major feedbacks" (see ovals P and S in Figure 2).

Considerable effort went towards developing a truly iterative model set at IIASA that would dynamically encompass and unify a broad range of technical and economic features of the global energy system. Unfortunately, this was not achieved in the end, and so most fundamental relationships (such as global trade of resources) and critical trade-offs between major physical, economic, and environmental variables had to be assumed. The iteration in MMI served only to perturb this *a priori* structure. Therefore, any consistency that exists among the many variables of the energy scenarios is not due to the formal iteration process; it was already there (or not there) in the input assumptions. Indeed, various key assumptions were no doubt modified during the course of scenario development, but this was an informal, undocumented process carried out in the heads of the analysts, rather than the systematic procedure suggested in Figure 2 and in many statements in the documentation. See Wynne (1983) for further discussion.

5.2. Small Feasible Region

This subsection is somewhat speculative in places, and is offered as food for thought.

In addition to the observation that the iterations in MMI had no appreciable effect, there is another factor that is central to the understanding of the results presented in the earlier sections. Linear programming models such as MESSAGE optimize an objective function subject to various constraints. The set of points that satisfy all the constraints is called the feasible region, and in many of the MMI scenarios the feasible region is so small as to be effectively one point (Schrattenholzer, 1982). In these cases, the constraints are so restrictive that *they* (rather than the optimization) determine the solution. This effect was seen most clearly above in the case of primary energy, where certain constraints are almost identical to the scenario results. For secondary energy, the optimization is responsible for the order in which the supply technologies are chosen, and the constraints dictate the size of the contribution from each particular technology. Thus the constraints often serve as *contributions* from the various energy sources (which seems to violate the notion of a constraint*).

A major theorem in linear programming theory states that under very general conditions, the optimal solution occurs at a vertex on the boundary of the feasible region. For this reason, the constraints that define this vertex are necessarily binding. However, if the feasible region is non-trivial (i.e. larger than the neighborhood of a single point), then the solution is *not* essentially identical to the set-theoretic intersection of the constraints (i.e. the boundary of the feasible region), even though some constraints are necessarily binding and are therefore represented in the solution.

The fact that the feasible region was often very small may explain why "potential risks to life and health, environmental constraints, and potential climate impacts are not incorporated explicitly" into the scenarios (EIFW, p.397). It is a curious fact that MESSAGE *does* contain built-in constraints on emission levels "for each type of pollutant", as well as a constraint on pollu-

*It seems natural that *constraints* should be absolute upper limits, representing utmost extremes of the available options. Taken together, these would define a sizeable feasible region within which the actual *contribution* from each particular option would be determined by numerous criteria; eg. economic, environmental, institutional, political, etc. In principle, such an approach would permit the exploration of a great many "futures", but the difficulty with single-objective linear programming models is that they always produce extreme solutions, which are usually not realistic. For a review of what is done in practice to deal with this problem, see Zalai (1982).

tion concentrations (EIFW, p.415). However, "these constraints, although available, were not directly used in the MESSAGE runs" (EIFW, footnote on p.415). As pointed out in one of the research reports, "Constraining the range of these variables means a reduction of the feasible region" (Schrattenholzer, 1981). Thus in some of the MMI scenarios, it is likely that if these environmental constraints had been included, the tiny feasible region would have vanished altogether (precluding the existence of the scenarios in their present form).

It is possible that a small feasible region was perceived to be desirable, because it might lessen the effects of the inherent instability with respect to certain input data (such as cost assumptions). Observe that a small feasible region could introduce a kind of pseudo-robustness, because some variables might be held almost constant with respect to variations in the input data that determine the objective function.* However, such an approach would defeat the purpose of the model, because the decision about where to locate the reduced feasible region in state space is arbitrary, and yet it is this subjective decision that largely determines the solution. Furthermore, the constraints themselves are arbitrary and uncertain. Variations in the constraints can cause the feasible region either to expand, in which case the intrinsic sensitivity problems become more apparent, or to disappear, in which case the solution ceases to exist.

A final remark concerns the possibility of replacing the single-objective function in MESSAGE with a more realistic multi-objective function. As one of many examples, it might be desirable to attempt simultaneous minimization of total cost and total pollution. However, if the constraints are such that the feasible region is very small, such an approach does not appear to be

*This point was clarified in discussions with Philippe Martin.

worthwhile, because all feasible solutions are approximately equivalent (Kok, 1983). Thus the optimal solution under the multi-objective function would not be much different from the original one (regardless of the degree of sophistication in the multi-objective function).

5.3. New Representation of MMI

In EIFW, there are a few cryptic hints that the constraints were "often quite tight" (p. 402), or that "these constraints, taken together, are the singular characteristics of the scenarios" (p.527). There are also statements that the feedback loops were operated manually (see Section 1). However, the reader is not likely to realize from such statements that the iterative model loop was almost completely ineffectual.

Recently, a new representation of the process that was used to develop the IIASA energy scenarios has appeared, as shown in Figure 16. This figure was first published in April 1983 (Sassin *et al*, 1983). Note the minor role played by the models MEDEE-2, MESSAGE, and IMPACT. Meanwhile, the actual iteration that was done is seen to be an informal process which was external to the set of energy models. In fact, the models themselves were used primarily in the capacity of accounting aids. See Wynne (1983) for further discussion and analysis of these issues.

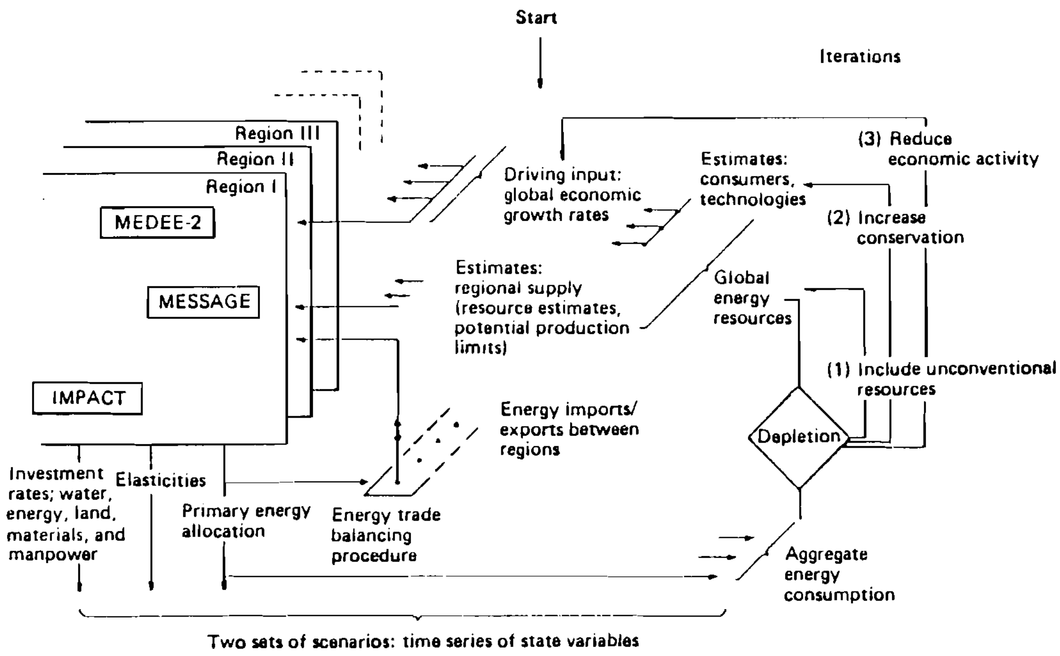


FIGURE 2.2 The process of scenario writing: the IIASA global High and Low Scenarios.

FIGURE 16 The process of scenario writing for the IIASA global high and low scenarios, as now described by the IIASA Energy Group (taken from Sassin *et al.* 1983). Note the minor role played by the models.

6. CONCLUSIONS

> Together, the scenarios, the alternative cases, and the sensitivity analyses should build a broad enough understanding of the energy problem and a set of sufficiently specific facts so that conclusions and recommendations for the energy transition can be formulated.
>
> — *Energy in a Finite World*, Vol. 2, p.395

Two analytic findings are established in this paper regarding the IIASA global high and low energy scenarios. The analysis in Section 3 shows that the important dynamic contents of the scenarios are effectively prescribed (before the computer is ever turned on) in the form of input assumptions that are fed into the mathematical energy models. Meanwhile, the computerized models themselves perform a simple heuristic analysis that reproduces various input assumptions with few alterations. Thus the models serve primarily as an accounting framework for displaying the hypotheses and assumptions of the analyst.

The second major finding is that the IIASA scenarios are structurally brittle with respect to minor changes in various assumed input data. It is shown in Section 4 that the energy supply mix in the scenarios is strongly dependent on arbitrary (and, in some cases, unlikely) assumptions about the future costs and availability of energy resources and supply technologies. Small changes in these assumptions (such as increased costs that have already been observed in reality) can yield extremely different scenarios from the models. This inherent lack of robustness precludes the possibility of drawing reliable conclusions or inferring major trends from the energy supply scenarios.

In addition to these analytic findings, it was observed that most of the key quantitative assumptions are presented with little or no substantiation or detailed clarification as to how they were obtained. Furthermore, there are no documented tests which explore the sensitivity of the final quantitative results to variations in a number of crucial input assumptions.

Finally, quite apart from the quality or utility of the quantitative scenarios themselves, there are disturbing elements in the published representation of the work. Several instances of mis-documentation and/or omissions have been noted, some of which leave the reader with incorrect impressions about what was actually done. For further discussion and analysis, see Wynne (1983).

Before drawing the final conclusions in this paper, a remark is in order concerning modeling. The analysis performed by MMI turned out to be highly simplistic and largely reproducible with a hand calculator. This demonstrates that a big, sophisticated computer model is not necessarily more accurate or "correct" than a small, uncomplicated model. Of course, large, complex models are necessary in many applications. However, when modeling a fundamentally unknowable system (such as the world's energy future), the collective error that could result from combining hundreds of individual assumptions, each of which is unverifiable, may be enormous. In any case, a great deal of human effort and money goes into developing large models such as MMI, and if the same task can be done much more simply, this is an important finding.

The overall conclusion in this paper is that the IIASA energy scenarios are based on tentative predictions and arbitrary assumptions that have not been carefully substantiated or tested. While it is perhaps reasonable to assume (or hope) that the future will be free of major political and economic surprises, this does not warrant the presumption of perfect information about the future.* Had there been extensive sensitivity analysis to ensure that the scenarios were indeed robust, then at best they might constitute a conjecture.

* In addition, before applying an analytical tool to project the future, it seems natural to determine if it can reproduce historical data, particularly in the case of energy developments after 1973. This was apparently not done in MMI.

However, a few simple tests reveal that the scenarios are unstable with respect to minor changes in various assumptions, and at least some such changes are certain to occur in the coming half-century. Hence there is no scientific basis for claiming that the scenarios or the conclusions drawn from them are robust. In view of these considerations, the scenarios must be regarded as opinion, rather than objective analysis of the factual basis of the world's energy future from which robust conclusions may be formulated.

Nevertheless, a number of "robust" conclusions or observations have been drawn from the scenarios and widely publicized in the literature and in numerous lectures (e.g., Häfele 1980a, 1983a,b). There are certain caveats in EIFW regarding some of these conclusions, but these are not emphasized in articles and speeches. Although scenarios are not presented as decisive forecasts, there is an inevitable tendency to view them as such, even by their authors.* This is revealed in the assertion that "*Our scenarios are globally comprehensive and allow for no escape*." (EIFW, p. 785, original italics)

One of the robust conclusions drawn from the scenarios is that the world will consume "unprecedented amounts" of dirty fossil fuels, such as tar sands and oil shale. 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 the scenarios. Nevertheless, this conclusion is claimed to be robust.

*For further discussion of this, see Schwarz and Hoag (1982) and Landsberg (1982).

Another example is provided by the future role of nuclear power: "by 2030 nuclear power (LWRs and FBRs) has a total of 8.09 TWyr/yr for the high scenario and 5.17 TWyr/yr for the low scenario. Its relative share is close to 23% in either case" (Häfele, 1983a). As observed above, this conclusion is based on tentative assumptions about relative costs of electricity generation that are presumed to hold for the next 50 years. Not only have these assumptions already proven to be incorrect, but once again no explicit account has been taken of key factors such as constraints on capital (to say nothing of the host of unresolved political and technical issues associated with nuclear power). Nevertheless, this contribution from nuclear power is claimed to be a robust observation derived from the scenarios (Häfele, 1983a). It is interesting to note what would be required of the world in order to fulfill this particular conclusion: we must complete, on the average, the equivalent of a brand new 1000 MW nuclear power generating plant ***every four to six days*** for the next 50 years.* This is characterized in the *Science* article as a "medium-size share" from nuclear power (Häfele, 1980a).

The practice of drawing conclusions from an analysis that does not support them is especially disturbing when the conclusions are used to influence policy decisions. A related example is discussed in Wynne (1983), involving a scientific study of electricity cost estimates which claimed to show a clear economic advantage favoring the FBR over the LWR (Grümm *et al.*, 1966). The study was used to justify a government expenditure of $96 million deutsche Marks for two prototype FBRs, and later it was found that certain input data had been tuned so as to create a particular impression that was favorable to the conclusions of the study (for full details see Keck 1981). If the quality of

*This means that, at present, a new 1000 MW facility would have to be brought on line every month, and this rate of construction would be steadily increased to reach a peak of one new power plant every two or three days by 2020 (see Appendix E).

decision making is to improve in the future, it is imperative that policy makers be provided with genuine and transparent assessments of each available option and its implications, rather than a set of strong recommendations that are based on shallow analysis and fond aspiration.

In closing, I wish to reiterate that many parts of the IIASA energy study have been important and valuable contributions to a greater understanding of the world's energy system. As for the scenarios themselves, perhaps we should heed a warning made almost 20 years ago (Schumacher, 1964).

> It is fashionable today to assume that any figures about the future are better than none. To produce figures about the unknown, the current method is to make a guess about something or other - called an "assumption" - and to derive an estimate from it by subtle calculation. The estimate is then presented as the result of scientific reasoning, something far superior to mere guesswork. This is a pernicious practice which can only lead to the most colossal planning errors, because it offers a bogus answer where, in fact, an entrepreneurial judgement is required.
>
> The study here under review employs a vast array of arbitrary assumptions, which are then, as it were, put into a calculating machine to produce a "scientific" result. It would have been cheaper, and indeed more honest, simply to assume the result.

APPENDICES

APPENDIX A: ESTIMATED RESEARCH EFFORT

The quoted figure of 225 person-years of effort comes from adding up the periods of service of each member of the Energy Systems Program, as listed on pp. v-x of EIFW. However, this figure does not include the efforts of 26 persons who participated intermittently, nor does it include the contributions of those persons who participated for less than one month. More importantly, the list includes participation only up through the end of 1979. However, the work of producing and promoting the documentation (EIFW Volumes 1, 2; several research reports, and DOGR) continued through all of 1980, much of 1981, and part of 1982. Considering these factors, the actual figure is significantly greater than 225.

It is very difficult to assess the amount of money spent on the IIASA Energy Program. The quoted figure of $6.5 million is a conservative estimate of the research budget alone; it does not include various administrative expenditures and overheads. In addition, it is not clear if the expenditures for the many conferences were paid for from the research budget or were drawn from other sources. Finally, the quoted figure does not include any expenditures during 1973 (because I was not able to obtain the data) or those after 1980. Considering all of these factors, the total expenditure for the IIASA Energy Program was undoubtedly much higher than the quoted research budget figure of $6.5 million.

The research budget is estimated using the figures given in the IIASA research plans for the years 1974-1980. These are converted to current US dollars using the average exchange rates for each of the years 1974 to 1980. The exchange rates are annual averages that were kindly furnished by the IIASA Budget Department.

Year	Total Research Budget (in millions of AS) for Energy Systems Program	Exchange rate (AS/US$)	Research Budget in current US$
1974	6.495	18.68	347700
1975	9.900	17.560	563800
1976	18.909	17.90	1056400
1977	21.610	16.514	1308600
1978	17.825	14.39	1238700
1979	14.154	13.364	1059100
1980	11.710	13.049	897400
totals	AS 100.603 million		US$6471700

APPENDIX B: SCENARIETTES FOR PRIMARY FOSSIL FUELS

In this Appendix we present the details of the scenariettes for coal, natural gas, and oil discussed in the text.

B.1. Coal

For coal in region III, the high scenariette is constructed from two sets of time series inputs supplied to MMI. These are the constraints labeled "Max annual coal extraction" and "Max annual coal imports" for the high scenario shown in Figure B.1, which is reproduced from DOGR (p.38). The domestic coal consumption in the scenariette is taken to be the first of these constraints. To determine the total quantity of domestic coal consumed by 2030 in the scenariette, we first add up the "Max. annual coal extraction" figures from 1980 to 2030, which gives 9175 GWyr/yr. Since there are 5 years in each time period, the total domestic coal consumed by 2030 is obtained by multiplying this figure by 5: (9175GWyr/yr)(5yr)= 45875 GWyr = 45.875 TWyr. To determine which cost categories are to be tapped in supplying this coal, we consult the input data. Figure B.2 is reproduced from the IIASA input data for region III (DOGR, p.37), from which we see that there are 92.9 TWyr of coal assumed to be available in the cheapest category (I). Since 45.875 < 92.9, all of the domestic coal in the scenariette will be taken from category I. Thus for the scenariette, which is displayed in Table B.1, the "Max. annual coal extraction" time series data are entered under category I (column (1) of the Table) and a column of

REGION III

Table 4. Primary energy resources and man-made fuels, time series data.

	Max. Annual Coal Extraction (GWyr) High	Low	Max. Annual Oil Extraction (GWyr) High	Low	Max. Annual Gas Extraction (GWyr) High	Low
1980	550	550	485	485	310	275
1985	600	600	515	515	320	250
1990	650	650	490	490	330	235
1995	725	725	455	450	340	220
2000	800	800	405	395	350	210
2005	900	900	365	345	350	195
2010	950	950	340	300	350	180
2015	1000	1000	320	260	350	160
2020	1000	1000	260	195	350	140
2025	1000	1000	295	125	350	110
2030	1000	1000	305	85	350	80

	Max. Annual Coal Imports (GWyr) High	Low	Max. Annual Oil Imports (GWyr) High	Low	Oil Import Costs ($/kWyr) High	Low	Gas Import Costs ($/kWyr) High & Low
1980	80	80	895	815	69	69	66
1985	210	170	995	835	87	87	73
1990	315	250	1105	885	106	96	80
1995	330	250	1230	955	106	96	88
2000	320	200	1365	1030	106	96	98
2005	300	100	1500	1115	106	96	107
2010	385	0	1370	1195	106	96	119
2015	805	0	1130	1270	106	96	119
2020	980	0	950	1345	106	96	119
2025	1280	0	840	1270	106	96	119
2030	1560	0	670	1200	106	96	119

FIGURE B.1 Fossil fuel input assumptions for the IIASA scenarios — region III (reproduced from DOGR, p.38).

zeroes is entered under category II (column (2)).

The imported coal in the scenariette is taken to be the "Max. annual coal imports" constraint, copied into column (3) of Table B.1. Finally, to obtain the total annual coal consumption in the scenariette, the contributions from categories I, II and imports are added together, to produce column (4) of the table. This completes the full specification of the coal scenariette, which essentially consists of just two sets of time series inputs, and their sum.

REGION III: Resources

Table 3. Primary energy resources and man-made fuels; general description.

		Coal	Oil	Gas	Natural Uranium	Plutonium
Indigenous Categories	Index of category	I	I	I	I	I
	Cost	\$27/kWyr	\$62/kWyr	\$62/kWyr	\$66/kg U_3O_8	
	Availability (over time horizon)	92.9TWyr	17.48TWyr	18.88TWyr	0.92Mt U_3O_8	n.a.
	Index of category	II	II	II	II	
	Cost	\$54/kWyr	\$103/kWyr	\$103/kWyr	\$110/kg U_3O_8	
	Availability (over time horizon)	151.4TWyr	3.3TWyr	4.72TWyr	2.4Mt U_3O_8	
	Index of category		III	III		
	Cost		\$129/kWyr	\$129/kWyr		
	Availability (over time horizon)		21.36TWyr	14.10TWyr		
	Index of category		IV	IV		
	Cost		\$250/kWyr	\$250/kWyr		
	Availability (over time horizon)		100TWyr	50TWyr		
Import Category	"Yes" if included	yes	yes	yes		
	Cost	\$36/kWyr	a)	a)		
	Availability (over time horizon)	b)	b)	100TWyr		
Export Cat.	"Yes" if included					

[a] Import costs vary over time; see time series data, Table 4.

[b] Annual amounts of imports are limited; there is no extra limit on the total amount.

FIGURE B.2 Natural resource input assumptions for the IIASA scenarios — region III (from DOGR, p.37).

Columns (1) and (4) of Table B.1 are plotted as curves in Figure 5 of the text, to give a graphical representation of the scenariette.

For a direct numerical comparison of the scenariette with the scenario, Figure B.3 is a copy of the final computer printout for coal consumption in the IIASA high scenario for region III. In this figure there are two rows of numbers, each row having three columns of time series data. The upper row gives the

TABLE B.1 Scenariette for coal consumption -- region III high.

Year	(1) Domestic Coal Category I	(2) Domestic Coal Category II	(3) Imported Coal	(4) Total Coal Consumption
1980	550.0	0.0	80.0	630.0
1985	600.0	0.0	210.0	810.0
1990	650.0	0.0	315.0	965.0
1995	725.0	0.0	330.0	1055.0
2000	800.0	0.0	320.0	1120.0
2005	900.0	0.0	300.0	1200.0
2010	950.0	0.0	385.0	1335.0
2015	1000.0	0.0	805.0	1805.0
2020	1000.0	0.0	980.0	1980.0
2025	1000.0	0.0	1280.0	2280.0
2030	1000.0	0.0	1560.0	2560.0

R3 REF W3H HI
DISAGGREGATION
OF COAL

1980	550.00000	0.00000	80.00000
1985	600.00000	0.00000	200.99951
1990	650.00000	0.00000	278.60449
1995	725.00000	0.00000	276.64636
2000	800.00000	0.00000	262.71597
2005	900.00000	0.00000	239.85030
2010	950.00000	0.00000	338.84589
2015	1000.00000	0.00000	669.28448
2020	1000.00000	0.00000	980.00000
2025	1000.00000	0.00000	1280.00000
2030	1000.00000	0.00000	1555.73853

	◆ COAL 1	X COAL 2	A COALIM
1980	550.00000	550.00000	630.00000
1985	600.00000	600.00000	800.99951
1990	650.00000	650.00000	928.60449
1995	725.00000	725.00000	1001.64636
2000	800.00000	800.00000	1062.71594
2005	900.00000	900.00000	1139.85034
2010	950.00000	950.00000	1288.84595
2015	1000.00000	1000.00000	1669.28455
2020	1000.00000	1000.00000	1980.00000
2025	1000.00000	1000.00000	2280.00000
2030	1000.00000	1000.00000	2555.73853

FIGURE B.3 Coal consumption results from the IIASA energy scenario — region III high.

individual contributions in the scenario from each category of coal (category I, category II, and imports). The lower row presents the same data in cumulative form, so that the last column of time series data (in the lower right hand corner) is the total coal consumption in the scenario. This format is standard in the IIASA computer printout and it applies to all computer printouts shown in this report.

The data in the first and third columns of the bottom row of Figure B.3 are plotted as points in Figure 5 of the text. It is clear from the data (or the figure) that the scenario and scenariette are in close agreement.

B.2. Natural Gas

The scenariette for natural gas is obtained in almost the exact same manner as that for coal, but there is a minor difference for imports. The time series data for annual gas imports comes from the assumed "Annual gas exports" time series inputs to region II, shown in Figure B.4 (reproduced from DOGR, p.24). Since region II is the only region allowed to export gas (by assumption, see DOGR), and region III is the only region allowed to import gas (by assumption, see Figure B.2), then all of region II's gas exports must go to region III. These add up to a total of 15.45 TWyr, which is less than the 100 TWyr available (see Figure B.2). The cost of imported gas reaches \$119/kWyr (by assumption, see Figure B.1), which is less than the assumed cost of coal gasification (\$125/kWyr, see Figure 1 of the text). Therefore, in the scenariette, there is no coal gasification (called "advgas" in Figure B.5).

The total quantity of domestic gas consumed by 2030 in the scenariette is 18.75 TWyr, which is less than the 18.88 TWyr of gas assumed to be available in category I. Thus in the scenariette, no gas is extracted from categories II, III, and IV.

REGION II

Table 4. Primary energy resources and man-made fuels, time series data.

	Max. Annual Coal Extraction (GWyr)		Max. Annual Oil Extraction (GWyr)		Max. Annual Gas Extraction (GWyr)		Annual Coal Exports (GWyr)		Annual Gas Exports (GWyr)	
	High	Low	High	Low	High	Low	High	Low	High	Low
1980	875	780	710	700	465	460	50	10	10	40
1985	1115	1020	730	700	625	610	100	90	65	95
1990	1380	1250	770	730	770	750	140	150	135	145
1995	1560	1410	800	740	915	900	130	180	210	185
2000	1675	1460	820	750	1045	1020	115	165	265	225
2005	1755	1350	850	760	1155	1120	90	60	320	260
2010	1925	1260	840	800	1225	1180	190	0	330	265
2015	2235	1350	730	770	1320	1270	290	5	375	300
2020	2660	1370	730	740	1435	1350	500	10	420	340
2025	3070	1430	730	700	1545	1440	650	10	460	385
2030	3570	1540	730	650	1660	1520	825	10	500	435

FIGURE B.4 Gas export assumptions (circled) for the IIASA scenarios — region II high (from DOGR, p.24).

R3 REF W3H HI
GASEOUS FUEL SUPPLY
BY TECHNOLOGY

1980	310.00000	0.00000	0.00000	0.00000	2.10319	0.00000
1985	320.00000	0.00000	0.00000	0.00000	64.31005	0.00000
1990	330.00000	0.00000	0.00000	0.00000	132.18433	0.00000
1995	340.00000	0.00000	0.00000	0.00000	210.19048	0.00000
2000	350.00000	0.00000	0.00000	0.00000	262.69733	0.00000
2005	350.00000	0.00000	0.00000	0.00000	315.68076	0.00000
2010	350.00000	0.00000	0.00000	0.00000	328.00000	0.00000
2015	350.00000	0.00000	0.00000	0.00000	374.40616	0.00000
2020	350.00000	0.00000	0.00000	0.00000	416.00000	0.00000
2025	350.00000	0.00000	0.00000	0.00000	459.00000	0.00000
2030	350.00000	0.00000	0.00000	0.00000	501.00000	0.00000

	◆ GAS1	X GAS2	A GAS3	> GAS4	V GASIMP	< ADVGAS
1980	310.00000	310.00000	310.00000	310.00000	312.10318	312.10318
1985	320.00000	320.00000	320.00000	320.00000	384.31006	384.31006
1990	330.00000	330.00000	330.00000	330.00000	462.18433	462.18433
1995	340.00000	340.00000	340.00000	340.00000	550.19049	550.19049
2000	350.00000	350.00000	350.00000	350.00000	612.69733	612.69733
2005	350.00000	350.00000	350.00000	350.00000	665.68079	665.68079
2010	350.00000	350.00000	350.00000	350.00000	678.00000	678.00000
2015	350.00000	350.00000	350.00000	350.00000	724.40619	724.40619
2020	350.00000	350.00000	350.00000	350.00000	766.00000	766.00000
2025	350.00000	350.00000	350.00000	350.00000	809.00000	809.00000
2030	350.00000	350.00000	350.00000	350.00000	851.00000	851.00000

FIGURE B.5 Gaseous fuel supply results from the IIASA scenario — region III high.

The natural gas scenariette is shown in Table B.2. The data in this table are plotted as curves in Figure 6 of the text. Meanwhile, the scenario results themselves are shown in Figure B.5 (plotted as points in Figure 6 of the text). The two agree very closely.

TABLE B.2. Scenariette for natural gas consumption -- region III high.

	Domestic Gas Category I	Domestic Gas Categories (II, III, IV) advgas	Imported Gas	Total Gas Consumption
1980	310.0	0.0	10.0	320.0
1985	320.0	0.0	65.0	385.0
1990	330.0	0.0	135.0	465.0
1995	340.0	0.0	210.0	550.0
2000	350.0	0.0	265.0	615.0
2005	350.0	0.0	320.0	670.0
2010	350.0	0.0	330.0	680.0
2015	350.0	0.0	375.0	725.0
2020	350.0	0.0	420.0	770.0
2025	350.0	0.0	460.0	810.0
2030	350.0	0.0	500.0	850.0

B.3. Oil

The oil scenariette is obtained in the same manner as the above two scenariettes, with one important difference. In this case, the total domestic oil consumed by 2030 in the scenariette is 21.175 TWyr. This figure is obtained by adding together the time series assumptions shown in Figure B.1 for "Max. annual oil extraction," and multiplying by 5. From Figure B.2 we see that there are 17.48 TWyr* of oil in category I, which is insufficient to supply all the oil consumed in the scenariette. Adding the category II oil to category I, we have 17.48 + 3.3 = 20.78 TWyr, which is still insufficient to satisfy the 21.175 TWyr consumed in the scenariette. Thus the scenariette will use all the oil of

*In the first draft of DOGR, this figure is misprinted as 11.48 TWyr.

categories I and II, and then dip into category III oil. To determine when the category transitions occur in the scenariette, we first compute the cumulative oil consumption as shown in Table B.3. Column (1) of this table is the "Max. annual oil extraction" constraint copied from Figure B.1. Viewing this column as a step function in time, column (2) of the table is its integral, converted to TWyr. For example, in the year 2005, the calculation has the form:

$$(365\ \text{GWyr/yr})(5\text{yr})(0.001\ \text{GWyr/TWyr}) + 11.75\ \text{TWyr} = 13.58\ \text{TWyr}\ .$$

TABLE B.3. Cumulative oil consumption in scenariette -- region III high.

	(1) Domestic oil consumption (GWyr/yr)	(2) Cumulative oil consumed (TWyr)	
1980	485.0	2.43	
1985	515.0	5.00	
1990	490.0	7.45	
1995	455.0	9.73	
2000	405.0	11.75	
2005	365.0	13.58	
2010	340.0	15.28	
2015	320.0	16.88	
2020	260.0	18.18	← end category I (17.48 TWyr)
2025	295.0	19.65	
2030	305.0	21.18	← end category II (20.78 TWyr)

From Table B.3, we can see that the first category transition occurs during the 2020 time period. To determine the oil consumed from the different categories in this period, we prorate as follows. In the year 2020:

$18.18 - 17.48 = 0.70$ TWyr of category II oil

0.700 TWyr/5yr = 140 GWyr/yr category II oil

$(260 - 140)$ GWyr/yr = 120 GWyr/yr category I oil

A similar prorating is carried out for the year 2030:

$21.18 - 20.78 = 0.40$ TWyr of category III oil

0.40 TWyr/5yr = 80 GWyr/yr category III oil

$(305 - 40)$ GWyr/yr = 225 GWyr/yr category II oil

Given these prorations, the oil scenariette is specified as shown in Table B.4 (plotted as curves in Figures 3 and 4 of the text).

For comparison with the scenario, Figure B.6 is reproduced from the computer printout for crude oil supply in the IIASA high scenario for region III. The "advliq" column refers to liquefied coal, which is treated in the scenariette for liquid fuel supply discussed in Appendix C. Thus the "total crude oil" supply column in Table B.4 should be compared with the circled column in Figure B.6. The column labeled "KONS1" in the figure refers to a slack variable in the linear program, and has no physical significance.

B.4. World Oil Supply

The world oil supply scenariette shown in Figure 13 of the text is obtained by adding the contributions from the high scenariettes for the individual regions I, III, IV, V, and VI. The domestic oil scenariettes in the individual regions are each obtained in precisely the same manner as just described for region III. Regions II and VII are not included because of the assumption (by the IIASA team) that these regions do not participate in interregional oil trade.

An additional source of liquid fuel is included in this scenariette: liquefied coal. This is incorporated as follows. It is assumed in the scenariette that if a region has more indigenous coal than oil, then coal liquefaction is pursued to the maximum extent allowed by the supply constraint. On the other hand, if a region has much more oil than coal, then coal liquefaction is assumed to be unnecessary, and hence not pursued at all in that region. Table B.5 shows the ratios of total oil resources to total coal resources for the oil trading regions. In computing these ratios, the contributions (given in DOGR) from all categories of domestic oil and coal are included (but not imports). For exam-

TABLE B.4 Scenariette for crude oil - region III high.

	Domestic Oil GWyr/yr			Imported Oil	Total crude oil supply
	Cat. I	Cat. II	Cat. III	(GWyr/yr)	(GWyr/yr)
1980	485.0	0.0	0.0	895.0	1380.0
1985	515.0	0.0	0.0	995.0	1510.0
1990	490.0	0.0	0.0	1105.0	1595.0
1995	455.0	0.0	0.0	1230.0	1685.0
2000	405.0	0.0	0.0	1365.0	1770.0
2005	365.0	0.0	0.0	1500.0	1865.0
2010	340.0	0.0	0.0	1370.0	1710.0
2015	320.0	0.0	0.0	1130.0	1450.0
2020	120.0	140.0	0.0	950.0	1210.0
2025	0.0	295.0	0.0	840.0	1135.0
2030	0.0	225.0	80.0	670.0	975.0

R3 REF W3H HI
LIQUID FUEL SUPPLY
CRUDE OIL EQU

1980	485.00000	0.00000	0.00000	0.00000	834.99854	0.00000	0.00000
1985	515.00000	0.30000	0.00000	0.00000	924.87628	0.00000	0.00000
1990	490.00000	0.00000	0.00000	0.00000	1072.61414	0.00000	0.00000
1995	455.00000	0.00000	0.00000	0.00000	1225.84705	0.00000	0.00000
2000	405.00000	0.00000	0.00000	0.00000	1361.34497	22.62857	0.00000
2005	365.00000	0.00000	0.00000	0.00000	1424.17432	95.42571	0.00000
2010	340.00000	0.00000	0.00000	0.00000	1370.00000	268.56003	0.00000
2015	320.0000H	0.00000	0.00000	0.00000	1130.00000	608.48004	0.00000
2020	121.00000	139.00000	0.00000	0.00000	950.00000	907.20001	6.08000
2025	0.00000	260.16983	0.00000	0.00000	840.00000	1078.19019	0.00000
2030	0.00000	260.83017	37.92983	0.00000	670.00000	1258.20007	0.00000

	+ DOHCRD	X OIL2	A OIL3	> OIL4	V IMPORT	< ADVLIQ	. + KONS1
1980	485.00000	485.00000	485.00000	485.00000	1319.99854	1319.99854	1319.99854
1985	515.00000	515.00000	515.00000	515.00000	1439.87634	1439.87634	1439.87634
1990	490.00000	490.00000	490.00000	490.00000	1562.61414	1562.61414	1562.61414
1995	455.00000	455.00000	455.00000	455.00000	1680.84705	1680.84705	1680.84705
2000	405.00000	405.00000	405.00000	405.00000	1766.34497	1788.97351	1788.97351
2005	365.00000	365.00000	365.00000	365.00000	1789.17432	1884.59998	1884.59998
2010	340.00000	340.00000	340.00000	340.00000	1710.00000	1978.56006	1978.56006
2015	320.0000H	320.00000	320.00000	320.00000	1450.00000	2058.47998	2058.47998
2020	121.00000	260.00000	260.00000	260.00000	1210.00000	2117.19995	2123.28003
2025	0.00000	260.16983	260.16983	260.16983	1100.16980	2178.36011	2178.36011
2030	0.00000	260.83017	298.76001	298.76001	968.76001	2226.96021	2226.96021

FIGURE B.6 Crude oil supply results from the IIASA scenario — region III high.

ple, using the data shown in Figure B.2, the calculation for region III is

$$(17.48 + 3.3 + 21.36 + 100.0)/(92.9 + 151.4) = 0.582$$

Note that for three of the regions, the oil/coal ratio is less than unity, so it is assumed that coal liquefaction is pursued in these cases. In the scenariettes for these regions, the contribution from liquefied coal is simply set equal to the assumed maximum supply constraint for this technology. Meanwhile, in regions IV and VI, there is at least an order of magnitude more oil than coal, so it is assumed in the scenariette that neither of these regions will pursue coal liquefaction.

TABLE B.5 Relative endowments of oil and coal resources.

Region	Resource ratio oil/coal	Coal liquefaction
I	0.28	yes
III	0.58	yes
IV	10.0	no
V	0.59	yes
VI	398.0	no

The scenariette for world oil supply is shown in Table B.6. The figures in this table are obtained by first adding together the contributions to each category (I, Ia, II, III) from the high oil scenariettes in regions I, III, IV, and V. Each of these regional scenariettes is obtained directly from the input assumptions (DOGR, pp. 13-14, 37-38, 48-49, 60-61) in precisely the same manner as the oil scenariette described above for region III. Then, added to this are the contributions from liquefied coal (regions I, III, V). To obtain these, the assumed maximum (secondary) supply constraints (DOGR, pp. 18, 42, 68) are converted to crude oil (primary) equivalent units by multiplying by the assumed crude oil/liquid fuel ratio of 1.08 (DOGR, p.99). Finally, the scenariette is completed by adding the contribution from region VI (which is just the assumed oil extraction constraint, DOGR, p.73). Note that the figures in Table B.6 are given in *cumulative* form. For example, in 2010, the contribution from regions I, III, IV and V to category II is 660 GWyr/yr, which is added to 2400 GWyr/yr to produce 3060 GWyr/yr, as shown in the table. The data in this table are plotted as curves in Figure 13 of the text.

TABLE B.6 World oil supply -- high scenariette.

	Category I	Category Ia	Category II	Category III	Liquefied Coal	Region VI
1980	1880					3210
1985	2080					3550
1990	2415					3885
1995	2645					4245
2000	2890				2946	4706
2005	1727	3010			3240	5430
2010	785	2400	3060		3698	6088
2015	640	1870	3095		4598	6988
2020	491	1936	3215		4782	7172
2025	470	2130	2585	3275	5434	7824
2030	695	2305	2791	3720	6418	8808

TABLE B.7 World oil supply – IIASA high scenario.

	Category I	Category Ia	Category II	Category III	Liquefied Coal	Region VI
1980	1801					2994
1985	2056					3312
1990	2352					3702
1995	2574					4158
2000	2685				2716	4477
2005	1757	2944			3100	5204
2010	908	2448	2955		3422	5787
2015	640	1833	2969		4041	6410
2020	491	1878	3115		4682	7069
2025	470	2064	2766	3221	5352	7798
2030	695	2504	2803	3640	6215	8621

For comparison with the scenariette, the IIASA scenario results are presented in Table B.7. The figures in this table are obtained by adding together the corresponding contributions from the high scenarios for regions

I, III, IV, V, and VI. The scenario results are taken directly from the computer printouts for liquid fuel supply (crude oil equivalent), which are reproduced in Figure B.6 for region III, Figure B.7 (regions I and IV), and Figure B.8 (regions V and VI).

B.5. Scenariettes for Low Scenario — Region III

The scenariettes for the low scenario in region III are obtained in the exact same manner as described above for the high scenario. Therefore, only the results are presented here (in graphical form). Figures B.9, B.10, and B.11 display comparisons of the scenariettes and scenarios for oil, natural gas, and coal, respectively. The first two figures exhibit close agreement between the scenariette and scenario. Observe in the final figure that the scenario trajectory for domestic coal dips below the scenariette starting in 2010, returning by 2030. This occurs because from 2010 onwards, coal-fired electricity is being rapidly displaced by nuclear energy. However, after 2020, the demand for synfuels drives the coal consumption back up to the constraint again by 2030. This is an example in which the constraint is not binding throughout the entire time horizon. If the scenariette and scenario are viewed as two different "predictions", this dip is not of great significance, primarily because it does not begin until 30 years off into the future, before which time the two "predictions" are identical.

(a)

Rerun
LIQUID FUEL SUPPLY
CRUDE OIL EQU

units; GW

1980	611,18	0,	0,	0.	450,00	0,	0,	0,
1985	685,00	0,	0,	0.	389,28	0,	0,	0.
1990	935,00	0,	0,	0,	155,80	0,	0,	0,
1995	1065.00	0,	0,	0,	89,52	0,	0,	0,
2000	1235,00	0,	0,	0,	0,	8,07	0,	0.
2005	90.82	1186,91	0,	0.	0,	51,74	0,	0,
2010	0.	755,09	507,13	0,	0,	166,63	0,	0,
2015	0,	0,	1136.43	0.	0,	391,77	0,	0.
2020	0.	0.	1098.36	0,	0,	523,80	0,	0,
2025	0.	0,	442,08	455,40	0,	815,40	0.	0,
2030	0,	0.	0,	837,07	0,	964,37	0,	0,

	+	x	a	>	v	<	+	x
	domcrd	oil2	oil3	oil4	import	advliq	kons1	export
1980	611.18	611.18	611,18	611.18	1061,18	1061,18	1061.18	1061.18
1985	685.00	685.00	685.00	685.00	1074,28	1074,28	1074,28	1074.28
1990	935,00	935,00	935,00	935.00	1090,80	1090,80	1090,80	1090.80
1995	1065,00	1065.00	1065.00	1065.00	1154,52	1154,52	1154,52	1154.52
2000	1235.00	1235.00	1235.00	1235.00	1235,00	1243.07	1243,07	1243.07
2005	90.82	1277.74	1277.74	1277.74	1277.74	1329.48	1329,48	1329.48
2010	0.	755.09	1262.21	1262.21	1262.21	1428.84	1428.84	1428.84
2015	0.	0.	1136.43	1136.43	1136.43	1528,20	1528.20	1528.20
2020	0.	0.	1098.36	1098.36	1098.36	1622.16	1622.16	1622.16
2025	0.	0.	442.08	897.48	897.48	1712.88	1712.88	1712.88
2030	0.	0.	0.	837.07	837.07	1801.44	1801.44	1801.44

(b)

Rerun Region 4 high
LIQUID FUEL SUPPLY
CRUDE OIL EQU

units: GW

1980	364.53	0.	0.	0.	0.	0.	0.	0.
1985	473.25	0.	0.	0.	0.	0.	0.	0.
1990	521.08	0.	0.	0.	0.	0.	0.	0.
1995	601.74	0.	0.	0.	0.	0.	0.	0.
2000	730.14	0.	0.	0.	0.	0.	0.	0.
2005	871.20	0.	0.	0.	0.	0.	0.	0.
2010	238.05	784.71	0.	0.	0.	0.	0.	0.
2015	0.	1193.40	0.	0.	0.	0.	0.	0.
2020	0.	1386.72	0.	0.	0.	0.	0.	0.
2025	0.	1594.08	0.	0.	0.	0.	0.	0.
2030	0.	1809.00	0.	0,	0.	0.	0.	0.

	+	x	a	>	v	<	+	x
	domcrd	oil2	oil3	oil4	import	advliq	kons1	export
1980	364,53	364,53	364,53	364,53	364,53	364,53	364,53	364,53
1985	473,25	473,25	473,25	473,25	473,25	473,25	473,25	473,25
1990	521,08	521.08	521,08	521,08	521,08	521,08	521,08	521,08
1995	601,74	601.74	601,74	601,74	601,74	601,74	601,74	601,74
2000	730.14	730.14	730,14	730,14	730,14	730,14	730,14	730,14
2005	871,20	871.20	871,20	871.20	871,20	871,20	871,20	871,20
2010	238.05	1022.76	1022,76	1022.76	1022,76	1022,76	1022.76	1022.76
2015	0.	1193.40	1193.40	1193,40	1193,40	1193,40	1193.40	1193.40
2020	0,	1386.72	1386.72	1386.72	1386,72	1386.72	1386.72	1386.72
2025	0.	1594.08	1594.08	1594.08	1594.08	1594.08	1594.08	1594.08
2030	0.	1809.00	1809.00	1809.00	1809.00	1809.00	1809.00	1809.00

FIGURE B.7 Crude oil supply results from the IIASA energy scenarios: (a) region I high; (b) region IV high.

(a)

units: GW

1980	340.69	0.	0.	0.	0.	0.	0.	0.
1985	383.04	0.	0.	0.	0.	0.	0.	0.
1990	406.54	0.	0.	0.	0.	0.	0.	0.
1995	453.33	0.	0.	0.	0.	0.	0.	0.
2000	495.00	0.	0.	0.	76.32	0.	0.	0.
2005	430.00	0.	0.	0.	267.14	9.18	0.	0.
2010	330.00	0.	0.	0.	499.55	31.21	0.	0.
2015	320.00	0.	0.	0.	647.72	71.24	0.	0.
2020	370.00	0.	0.	0.	737.71	136.45	0.	0.
2025	470.00	0.	0.	0.	758.63	236.93	0.	0.
2030	695.00	0.	0.	0.	644.99	352.37	0.	0.

	curve 1	curve 2	curve 3	curve 4	curve 5	curve 6	curve 7	curve 8
	+	x	a	>	v	<	+	x
	domcrd	oil2	oil3	oil4	import	advliq	kons1	export
1980	340.69	340.69	340.69	340.69	340.69	340.69	340.69	340.69
1985	383.04	383.04	383.04	383.04	383.04	383.04	383.04	383.04
1990	406.54	406.54	406.54	406.54	406.54	406.54	406.54	406.54
1995	453.33	453.33	453.33	453.33	453.33	453.33	453.33	453.33
2000	495.00	495.00	495.00	495.00	571.32	571.32	571.32	571.32
2005	430.00	430.00	430.00	430.00	697.14	706.32	706.32	706.32
2010	330.00	330.00	330.00	330.00	829.55	860.76	860.76	860.76
2015	320.00	320.00	320.00	320.00	967.72	1038.96	1038.96	1038.96
2020	370.00	370.00	370.00	370.00	1107.71	1244.16	1244.16	1244.16
2025	470.00	470.00	470.00	470.00	1228.63	1465.56	1465.56	1465.56
2030	695.00	695.00	695.00	695.00	1339.99	1692.36	1692.36	1692.36

(b)

Rerun Region 6 high
LIQUID FUEL SUPPLY
CRUDE OIL EQU

units: GW

1980	1192.96	0.	0.	0.	0.	0.	0.	0.
1985	1255.80	0.	0.	0.	0.	0.	0.	0.
1990	1349.64	0.	0.	0.	0.	0.	0.	0.
1995	1584.33	0.	0.	0.	0.	0.	0.	0.
2000	1760.00	0.	0.	0.	0.	0.	17.12	-15.85
2005	2103.72	0.	0.	0.	0.	0.	0.	0.
2010	2364.80	0.	0.	0.	0.	0.	0.	0.
2015	2368.76	0.	0.	0.	0.	0.	0.	0.
2020	2386.92	0.	0.	0.	0.	0.	0.	0.
2025	2390.00	0.	0.	0.	0.	55.88	0.	0.
2030	2390.00	0.	0.	0.	0.	16.32	0.	0.

	+	x	a	>	v	<	+	x
	domcrd	oil2	oil3	oil4	import	advliq	kons1	export
1980	1192.96	1192.96	1192.96	1192.96	1192.96	1192.96	1192.96	1192.96
1985	1255.80	1255.80	1255.80	1255.80	1255.80	1255.80	1255.80	1255.80
1990	1349.64	1349.64	1349.64	1349.64	1349.64	1349.64	1349.64	1349.64
1995	1584.33	1584.33	1584.33	1584.33	1584.33	1584.33	1584.33	1584.33
2000	1760.00	1760.00	1760.00	1760.00	1760.00	1760.00	1777.12	1761.27
2005	2103.72	2103.72	2103.72	2103.72	2103.72	2103.72	2103.72	2103.72
2010	2364.80	2364.80	2364.80	2364.80	2364.80	2364.80	2364.80	2364.80
2015	2368.76	2368.76	2368.76	2368.76	2368.76	2368.76	2368.76	2368.76
2020	2386.92	2386.92	2386.92	2386.92	2386.92	2386.92	2386.92	2386.92
2025	2390.00	2390.00	2390.00	2390.00	2390.00	2445.88	2445.88	2445.88
2030	2390.00	2390.00	2390.00	2390.00	2390.00	2406.32	2406.32	2406.32

FIGURE B.8 Crude oil supply results from the IIASA energy scenarios: (a) region V high; (b) region VI high.

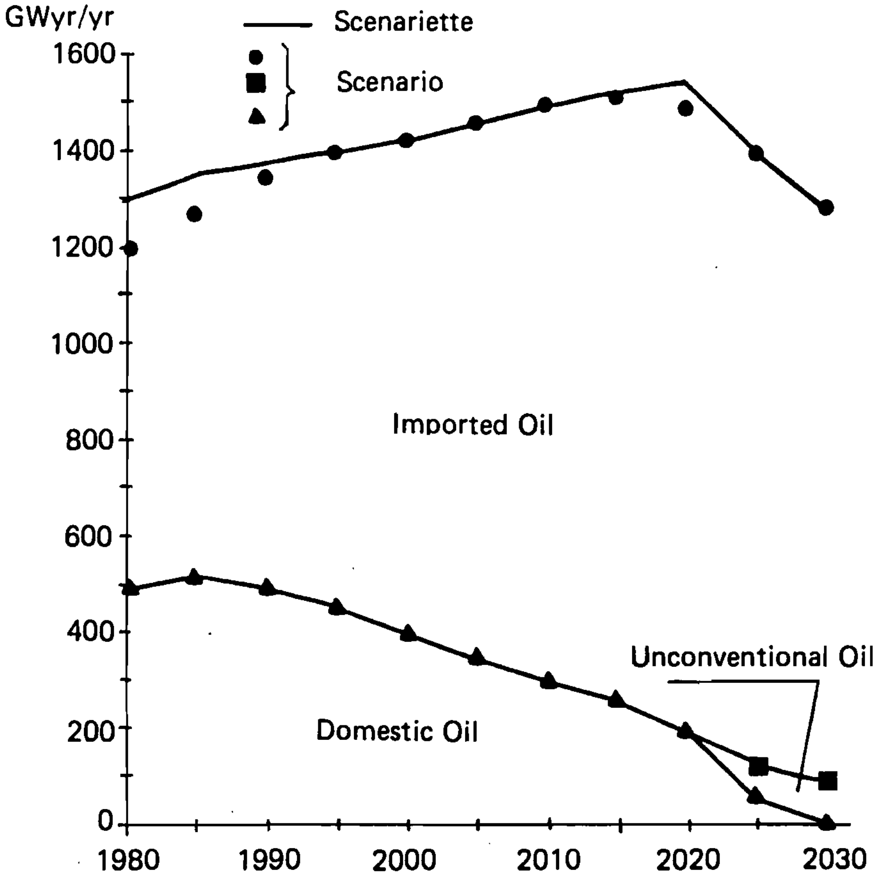


FIGURE B.9 Comparison of scenariette and scenario results for crude oil supply — region III low.

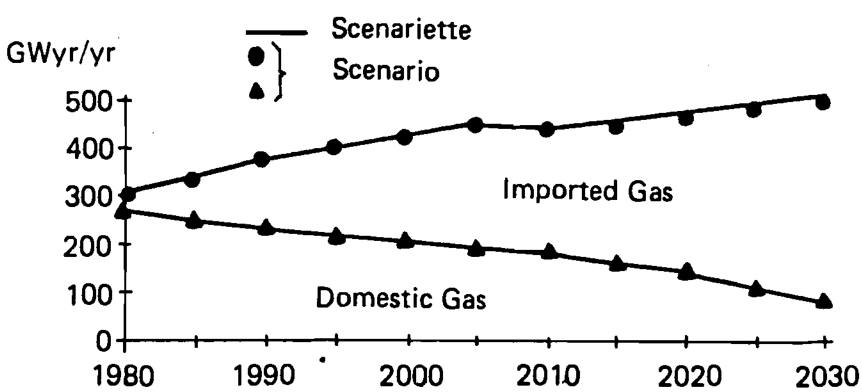


FIGURE B.10 Comparison of scenariette and scenario results for natural gas supply — region III low.

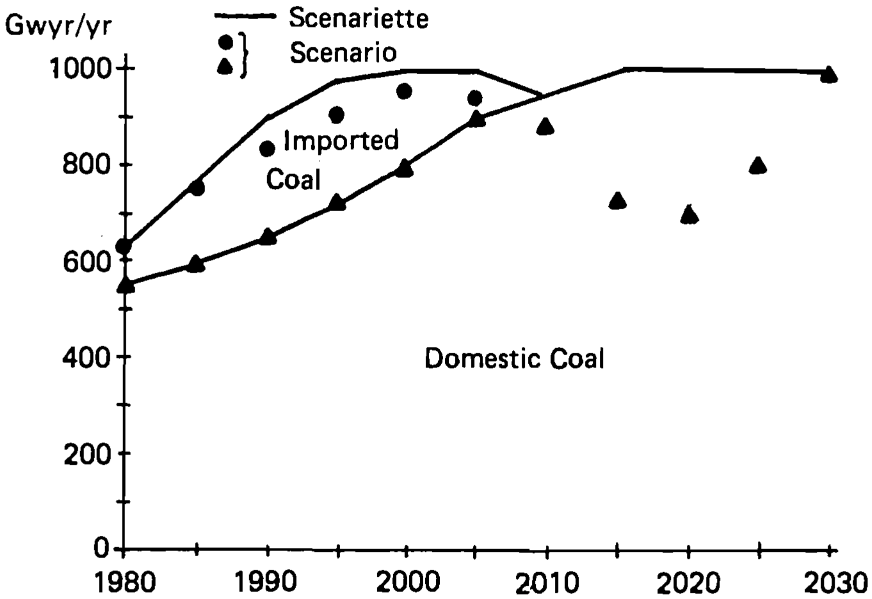


FIGURE B.11 Comparison of scenariette and scenario results for coal supply — region III low.

APPENDIX C: SCENARIETTES FOR SECONDARY ENERGY SUPPLY SYSTEMS

In this Appendix, the details of the secondary energy supply scenariettes are presented.

C.1. Liquid Fuel Supply

In developing the secondary energy supply scenariettes, we begin with the scenariette for liquid fuels. The reason for this is that it may be necessary to implement coal liquefaction in the scenariette for liquid fuels, and if so, this will limit the amount of coal available for electricity generation. It is assumed in the scenariette that the priority for coal use is to satisfy liquid fuel and solid fuel requirements first. The remaining coal is then available for electricity generation. The reason for this assumption is that electricity can be generated with a variety of technologies other than coal-fired power, whereas the use of coal may be the only available option in certain demand categories other than electricity.

As discussed in the text, the demand for secondary energy (electricity, liquid fuels, solid fuels, etc.) is taken from the "Secondary fuel mix and substitutions procedure" labeled D in Figure 2 of the text. These data (inputs to MESSAGE) are shown in Figure C.1, which is reproduced from DOGR (p.36). The approach in constructing this scenariette is to fulfill this demand as cheaply as possible. From Table 1 of the text, the cost of refined crude oil is \$75/kWyr, and the cost of liquefied coal is \$125/kWyr. The refined crude oil cost is for

REGION III

Table 2. Secondary energy demand (GWyr/yr).

	Electricity High	Electricity Low	Liquid Fuels High	Liquid Fuels Low	Solid Fuels High	Solid Fuels Low
1980	290	275	1145	1068	208	197
1985	354	321	1296	1148	235	212
1990	423	367	1428	1217	256	219
1995	496	412	1542	1275	271	220
2000	571	455	1645	1323	287	222
2005	646	497	1741	1363	307	228
2010	723	538	1830	1395	329	238
2015	802	578	1906	1417	351	247
2020	881	618	1967	1431	369	254
2025	963	659	2017	1438	384	259
2030	1045	699	2062	1444	397	263

	Gaseous Fuels High	Gaseous Fuels Low	Soft Solar High	Soft Solar Low	District Heat High	District Heat Low
1980	302	289	4	4	7	7
1985	359	326	9	9	15	13
1990	427	360	16	14	24	21
1995	501	390	23	20	35	30
2000	571	417	32	27	48	40
2005	631	443	40	34	61	51
2010	679	468	49	41	76	62
2015	722	489	59	48	91	74
2020	765	508	68	55	106	85
2025	808	525	77	62	122	97
2030	850	540	87	69	138	108

FIGURE C.1 Secondary energy demand projections for the IIASA scenarios — region III (from DOGR, p.36).

the case of category I oil. For other categories, the cost is determined as shown in Table C.1 (rounded to the nearest dollar). These costs are calculated from the cost equation (E.3) of Appendix E, using input assumptions given in DOGR (pp. 37,99). As an example, the cost of refined oil from category I is calculated as follows (see Appendix E for a full description of the formula used here):

$$\frac{(\$50/\,\mathrm{kW})(0.0708/\,\mathrm{yr})}{0.85} + \$3.7/\,\mathrm{kWyr} + (1.08\mathrm{kWyr}/\,\mathrm{yr})(\$62/\,\mathrm{kWyr})$$

$$= \$74.82/\,\mathrm{kWyr}$$

The times when these options become available are indicated in the table, based on the oil scenariette described in Appendix B for domestic oil (categories II and III), and the assumed supply constraint for coal liquefaction

TABLE C.1 Cost ranking for liquid fuel technologies.

Technology	Cost ($/kWyr)	Availability
Crude oil refinery (Cat. I)	75	
Crude oil refinery (Cat. II)	119	not before 2020
Crude oil refinery (Import)	122[a]	
Coal Liquefaction	125	from 2000 onwards
Crude oil refinery (Cat. III)	147	not before 2030

[a]This figure is $82 in 1980, $102 in 1985, and $122 thereafter (see oil import costs, Figure B.1).

(DOGR; Figure C.2). Given the cost ranking in Table C.1, it is clear that the category I oil is refined first, since it is the least costly. In the scenariette, the maximum allowable quantity of category I oil is refined, which is specified by the oil scenariette presented in Appendix B. The assumed conversion efficiency from crude oil to refined liquid fuel is 1.08 kWyr crude per kWyr refined (DOGR, p.99). Thus, dividing the scenariette results for consumption of category I oil (Table B.4) by 1.08, we obtain the contribution from category I oil to liquid fuel supply, shown in column (1) of Table C.2.

After category I oil, imported oil is refined in the scenariette, and this turns out to be sufficiently plentiful to meet the demand for liquid fuels up through 1995. The same conversion factor (1.08) is applied in converting the imported crude (Table B.4) to refined liquid fuel (column (5) of Table C.2). From 2000 onwards, the imports are not sufficiently abundant to meet the demand (see Figure C.1), so coal liquefaction is implemented. The contribution from liquefied coal is shown in column (6) of Table C.2. The calculation of this contribution in the year 2010, as an example, is as follows:

$$1830 \text{ GWyr/yr} - (315 + 1269) \text{ GWyr/yr} = 246 \text{ GWyr/yr}$$

To verify that the contribution from coal liquefaction is feasible, we first compare it with the assumed maximum supply constraint (Figure C.2), from which

NAME: advcoal, liquid, a (Coal Liquefaction)
1975 capacity 0.GW, growth parameter 0.%/yr.
Buildup parameters: γ = 2.00, g = 6.00GW/yr.

Table 10. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	0.	0.	0.
1985	0.	0.	0.
1990	0.	0.	0.
1995	0.	0.	0.
2000	6.00	30.	26.
2005	18.00	120.	102.
2010	42.00	330.	281.
2015	90.00	780.	663.
2020			840.
2025			1025.
2030			1165.

FIGURE C.2 Assumed supply constraints for coal liquefaction in the IIASA scenarios — region III (from DOGR, p.42).

we see that this level of production is feasible (except for the year 2020, when the constraint forces a slight reduction from 846 to 840). We next calculate the quantity of coal required. Since 1.67 kWyr of coal are required for each kWyr of liquid fuel produced (DOGR, p.93), the coal consumed by this technology is calculated by multiplying the contribution in the scenariette by 1.67. This produces column (2) in Table C.3. Also shown in the table are the requirements for solid fuels (see Figure C.1), and the quantity of coal that is left over (column (4)), which is available for electricity generation (if required). Column (4) is obtained by subtracting the sum of columns (2) and (3) from the total coal consumption in the scenariette (column (1), which is copied from column (4) of Table B.1 in Appendix B).

The final contribution in the liquid fuel scenariette comes from category II and category III oil (columns (2) and (3) of Table C.2). These are used after

TABLE C.2 Scenariette for liquid fuel supply (GWyr/yr) -- region III high.

Year	(1) Category I	(2) Category II	(3) Category III	(4) Category IV	(5) Imports	(6) Liquefied Coal
1980	449	0	0	0	829	0
1985	477	0	0	0	921	0
1990	454	0	0	0	1023	0
1995	421	0	0	0	1139	0
2000	375	0	0	0	1264	6
2005	338	0	C	0	1389	14
2010	315	0	0	0	1269	246
2015	296	0	0	0	1046	564
2020	111	130	0	0	880	840
2025	0	273	0	0	778	966
2030	0	208	74	0	620	1160

Cumulative:

1980	449	449	449	449	1278	1278
1985	477	477	477	477	1398	1398
1990	454	454	454	454	1477	1477
1995	421	421	421	421	1560	1560
2000	375	375	375	375	1639	1645
2005	338	338	338	338	1727	1741
2010	315	315	315	315	1584	1830
2015	296	296	296	296	1342	1906
2020	111	241	241	241	1121	1961
2025	0	273	273	273	1051	2017
2030	0	208	282	282	902	2062

TABLE C.3 Uses of coal (GWyr/yr) in the scenariette.

Year	(1) Maximum coal consumption	(2) Coal liquefaction	(3) Solid fuel	(4) Coal available for electricity generation
1980	630	0	208	422
1985	810	0	235	575
1990	965	0	256	709
1995	1055	0	271	784
2000	1120	10	287	823
2005	1200	23	307	870
2010	1335	411	329	595
2015	1805	942	351	512
2020	1980	1403	369	208
2025	2280	1613	384	283
2030	2560	1937	397	226

the oil in category I is depleted, following the oil scenariette (Appendix B). Once again, the primary to secondary conversion efficiency is assumed to be $1/1.08 = 0.926$.

In addition to showing the individual contributions from each technology, Table C.2 also displays the scenariette data in a cumulative form. The latter data are plotted as curves in Figure 10 of the text. The two rows of data in Table C.2 may be compared directly with the scenario results themselves, shown in Figure C.3, and plotted as points in Figure 10 of the text.

R3 REF W3H HI
LIQUID FUEL SUPPLY
SECONDARY ENERGY

1980	449.10999	0.00000	0.00000	0.00000	773.20862	0.00000	0.00000
1985	476.89001	0.00000	0.00000	0.00000	856.43542	0.00000	0.00000
1990	453.73999	0.00000	0.00000	0.00000	993.24066	0.00000	0.00000
1995	421.32999	0.00000	0.00000	0.00000	1135.13440	0.00000	0.00000
2000	375.03000	0.00000	0.00000	0.00000	1260.60547	20.95238	0.00000
2005	337.98999	0.00000	0.00000	0.00000	1318.78540	88.35714	0.00000
2010	314.84000	0.00000	0.00000	0.00000	1268.62000	248.66667	0.00000
2015	296.32001	0.00000	0.00000	0.00000	1046.38000	563.40741	0.00000
2020	112.04600	128.71400	0.00000	0.00000	879.70001	840.00000	5.62963
2025	0.00000	240.91727	0.00000	0.00000	777.84003	998.32422	0.00000
2030	0.00000	241.52873	35.12302	0.00000	620.41998	1165.00000	0.00000

	+ DOMCRD	X OIL2	A OIL3	> OIL4	V IMPORT	< ADVLIQ	+ KONS1
1980	449.10999	449.10999	449.10999	449.10999	1222.31860	1222.31860	1222.31860
1985	476.89001	476.89001	476.89001	476.89001	1333.32544	1333.32544	1333.32544
1990	453.73999	453.73999	453.73999	453.73999	1446.98071	1446.98071	1446.98071
1995	421.32999	421.32999	421.32999	421.32999	1556.46436	1556.46436	1556.46436
2000	375.03000	375.03000	375.03000	375.03000	1635.63550	1656.58789	1656.58789
2005	337.98999	337.98999	337.98999	337.98999	1656.77539	1745.13257	1745.13257
2010	314.84000	314.84000	314.84000	314.84000	1583.45996	1832.12659	1832.12659
2015	296.32001	296.32001	296.32001	296.32001	1342.70007	1906.10754	1906.10754
2020	112.04600	240.76001	240.76001	240.76001	1120.46008	1960.46008	1966.08972
2025	0.00000	240.91727	240.91727	240.91727	1018.75732	2017.08154	2017.08154
2030	0.00000	241.52873	276.65176	276.65176	897.07178	2062.07178	2062.07178

FIGURE C.3 Liquid fuel supply results from the IIASA scenarios — region III high.

C.2. Electricity Supply

The analysis in this case is essentially the same as for the liquid fuel supply scenariette. The electricity demand data are supplied to MESSAGE as an input, shown in Figure C.1 (from DOGR, p.36). The approach is again to fulfill this demand as cheaply as possible. Looking back at Table 1 of the text,

REGION III

NAME: hydro, elec, a (Hydro Power Plant)

1975 capacity 148.00GW, growth parameter 1.0%/yr.

Buildup parameters: γ = 0., g = 0.GW/yr.

Table 12. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	2.40	148.	74.
1985	2.60	149.	74.
1990	2.70	150.	75.
1995	2.75	150.	75.
2000	2.80	149.	75.
2005	2.80	148.	74.
2010	2.80	147.	73.
2015	2.80	144.	72.
2020	2.80	141.	70.
2025	2.80	136.	68.
2030	2.80	138.	69.

FIGURE C.4 Supply constraint assumptions for hydropower in the IIASA scenarios — region III (from DOGR, p.43).

hydropower is the least expensive technology, so it is used first. However, hydropower is available only in limited supply; thus the scenariette utilizes as much as possible. This maximum contribution from hydropower is spelled out in the input assumptions (Figure C.4) and copied into column (1) of Table C.4.

After hydropower, the next cheapest technologies are nuclear technologies: the light water reactor (LWR) and the fast breeder reactor (FBR). The input assumptions to MESSAGE include an upper bound on the total contribution from nuclear power, shown in Figure C.5 (from DOGR, p.40). In the scenariette, this full contribution is utilized, unless it (together with hydropower) exceeds the demand. The assumed maximum supply constraints for LWR and FBR are shown in Figure C.6 (from DOGR, pp.39,40). As shown in the figure, FBR is not an available option until the year 2000. Prior to that time, the LWR supply constraint exceeds the constraint on total nuclear energy; therefore the latter is taken to be the supply contribution from LWR up

TABLE C.4 Scenariette for electricity generation (GWyr/yr) -- region III high

(a) By technology:

Year	(1) Hydro	(2) LWR	(3) FBR	(4) Coal and other	(5) Maximum electricity from PCT
1980	74	33	0	183	151
1985	74	55	0	225	206
1990	75	90	0	258	254
1995	75	142	0	279	281
2000	75	212	7	277	295
2005	74	293	28	251	312
2010	73	385	77	188	213
2015	72	455	182	93	184
2020	70	412	399	0	75
2025	68	55	840	0	101
2030	69	0	976	0	81

(b) Cumulative:

1980	74	107		290
1985	74	129		354
1990	75	165		423
1995	75	217		496
2000	75	287	294	571
2005	74	367	395	646
2010	73	458	535	723
2015	72	527	709	802
2020	70	482	881	881
2025	68	123	963	963
2030	69	69	1045	1045

TABLE C.5 IIASA scenario for electricity generation (GWyr/yr) -- region III high.

Year	Hydro	LWR	FBR	Coal and other
1980	74	107		282
1985	74	130		355
1990	75	165		427
1995	75	217		501
2000	75	289	296	576
2005	74	367	395	653
2010	73	458	535	733
2015	72	495	677	815
2020	70	414	813	898
2025	68	339	891	982
2030	69	246	979	1067

REGION III

Table 6b. Upper limits on total nuclear energy, High case.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	3.94	48.	33.
1985	6.32	79.	55.
1990	10.00	128.	90.
1995	15.44	204.	142.
2000	23.06	313.	219.
2005	32.89	458.	321.
2010	44.36	660.	462.
2015	56.27	910.	637.
2020	67.22	1196.	837.
2025	43.70	1338.	936.
2030	54.30	1494.	1046.

FIGURE C.5 Assumed constraints on the total nuclear contribution for the IIASA high scenario — region III (from DOGR, p.40).

through 1995. This is shown in column (2) of Table C.4. These LWR data are used to calculate the uranium extraction scenariette in Appendix E, where it is shown that the assumed 0.92 Mt of cheap uranium (Figure B.2) is exhausted in 2005 (according to the uranium scenariette). Thus, the "LWR-step" occurs in 2005, and thereafter FBR is favored over LWR. Hence FBR is utilized at its maximum supply constraint after 2005.

To meet this maximum supply constraint, it is necessary that FBR be utilized to the maximum allowable extent prior to 2005 as well (due to the form of the constraint equation (1) in the text). Thus, from the year 2000 onwards, the scenariette utilizes the assumed maximum contribution from FBR (shown in Figure C.6), unless it exceeds the demand. This is indicated in column (3) of Table C.4. From 2000 onwards the contribution from LWR is simply the difference between the constraint on nuclear energy and the contribution from FBR. For example, in the year 2005, the assumed maximum contribution from nuclear power is 321 GWyr/yr (Figure C.5). Thus, the contribution from

REGION III:

NAME: u-lwr, elec, a (Light Water Reactor)

1975 capacity 28.00GW, growth parameter 25.00%/yr.

Buildup parameters: γ = 1.50, g = 2.00GW/yr.

Table 5. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	7.65	66.	46.
1985	13.48	133.	93.
1990	22.22	244.	171.
1995	35.33	418.	293.
2000	55.00	687.	481.
2005	84.50	1091.	764.
2010	128.75	1696.	1188.
2015	195.13	2605.	1823.
2020	294.69	3967.	2777.
2025	444.04	6011.	4207.
2030	668.06	9076.	6353.

NAME: p-fbr, elec, a (Fast Breeder Reactor)

1975 capacity 0.GW, growth parameter 0.%/yr.

Buildup parameters: γ = 2.00, g = 2.00GW/yr.

Table 7. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	0.	0.	0.
1985	0.	0.	0.
1990	0.	0.	0.
1995	0.	0.	0.
2000	2.00	10.	7.
2005	6.00	40.	28.
2010	14.00	110.	77.
2015	30.00	260.	182.
2020	62.00	570.	399.
2025	126.00	1200.	840.
2030	254.00	2460.	1722.

FIGURE C.6 Supply constraint assumptions for LWR and FBR in the IIASA scenarios — region III (from DOGR, pp.39,40).

LWR in the scenariette for that year is given by:

$$(321 - 28)\text{GWyr/yr} = 293 \text{ GWyr/yr}$$

as shown in column (2) of Table C.4.

NAME: coal, elec, a (Coal Fired Power Plant, Present Technology)

1975 capacity 199.00GW, growth parameter 4.00%/yr.

Buildup parameters: γ = 2.00, g = 2.00GW/yr.

Table 8. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/ry)
1980	22.49	292.	205.
1985	46.99	504.	353.
1990	95.97	955.	669.
1995	193.94	1890.	1323.
2000	389.89	3798.	2658.
2005	781.77	7655.	5359.
2010	1565.55	15371.	10759.
2015	3133.10	30801.	21561.
2020	6268.20	61662.	43164.
2025	12538.40	123385.	86369.
2030	25078.79	246829.	172780.

NAME: coal, coal, a (Coal Supply)

NAME: advcoal, elec, a (Advanced Coal-Fired Power Plant)

1975 capacity 0.GW, growth parameter 0.%/yr.

Buildup parameters: γ = 2.00, g= 2.00GW/yr.

Table 9. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	0.	0.	0.
1985	0.	0.	0.
1990	0.	0.	0.
1995	2.00	10.	7.
2000	6.00	40.	28.
2005	14.00	110.	77.
2010	30.00	260.	182.
2015	62.00	570.	399.
2030	126.00	1200.	840.
2025	254.00	2460.	1722.
2030	510.00	4980.	3486.

FIGURE C.7 Supply constraint assumptions for coal-fired electricity in the IIASA scenarios — region III (from DOGR, p.94).

The remaining gap between supply and demand is filled primarily with coal in the scenariette. The supply constraint for coal-fired power is clearly

R3 REF W3H HI
ELECTRICITY GENERATION
BY TECHNOLOGY

1980	33.34016	0.00000	147,31184	0.00000	74,12058	0,00000	27,52743
1985	55.30804	0.00000	202.86722	0.00000	74,46612	0,00000	21,95863
1990	89.84383	0.00000	242.86899	0.00000	74,74775	0,00000	19,43943
1995	142.46716	0.00000	261.80154	1.28800	74,82448	0,00000	21,01880
2000	211.85381	7.00000	260.87653	5.15200	74,67952	0,00000	16,53817
2005	292.77499	28.00000	232,57127	14,16800	74,17020	0,00000	11,31554
2010	385.24503	77.00000	171.99979	25,47727	73,27795	0,00000	0,00000
2015	422.55878	182.00000	111.39575	26.63998	71,98322	0,00000	0,42227
2020	343.55209	399.00000	24.63412	56.18832	70,26550	4.55993	0,00000
2025	271.32599	551.95001	48.78060	37.48026	68,10320	4.55993	0,00000
2030	176.41513	733.81201	15.21826	68,29181	69,10288	4,55993	0,00000

	+ LWR	X FBR	A COAL	> ADVCOL	V HYDRO	< SOLAR	+ PETG
1980	33.34016	33.34016	180.65201	180.65201	254,77260	254,77260	282,30002
1985	55.30804	55.30804	258.17526	258.17526	332,64139	332.64139	354,60001
1990	89.84383	89.84383	332.71283	332.71283	407,46057	407,46057	426,89999
1995	142.46716	142.46716	404.26871	405.55670	480.38120	480.38120	501.39999
2000	211.85381	218.85381	479.73035	484.88235	559.56189	559.56189	576,10004
2005	292.77499	320.77499	553.34625	567.51428	641,68451	641,68451	653,00006
2010	385.24503	462.24503	634.24481	659.72211	733.00006	733,00006	733,00006
2015	422.55878	604.55878	715,95453	742.59448	814,57770	814,57770	814,99994
2020	343.55209	742.55212	767,18622	823.37451	893,64001	898,19995	898,19995
2025	271.32599	823.27600	872,05658	909.53687	977.64008	982,20001	982,20001
2030	176.41513	910,22717	925,44543	993.73724	1062,84009	1067,40002	1067,40002

FIGURE C.8 Electricity generation results from the IIASA scenarios — region III high.

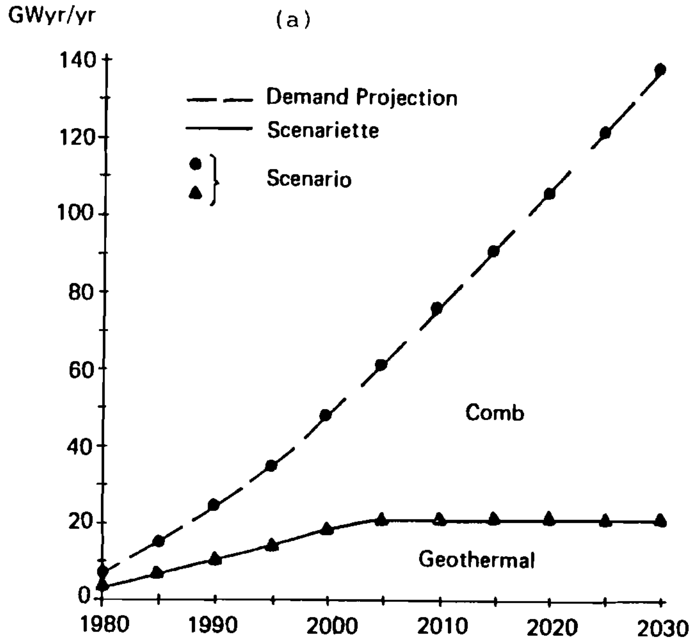
sufficient to meet this gap (see Figure C.7). As mentioned in the text, no distinction is made in the scenariette between present and advanced coal technologies for electricity generation. Using the fuel consumption of the present coal technology (PCT), which is 2.79 kWyr coal per kWyr of electricity generated (DOGR, p.94), we calculate the maximum quantity of electricity that can be produced (column (5) of Table C.4) with the remaining coal (shown in column (4) of Table C.3). By comparing columns (4) and (5) of Table C.4, it is clear that there is sufficient coal to fill the remaining gap between demand and supply after 1990. The small deficit before 1990 is made up with gas- or oil-fired plants (called "petg" in the IIASA scenarios). The scenariette is not specific about this, and all electricity produced from fossil fuels is simply lumped together into one category called "Coal and other". There are several reasons for this, the most important being that the small contributions from non-coal based generation are relatively insignificant when considering major trends in the supply scenarios. Another reason is that the electricity demand in MMI is divided into three specific load regions, which must be considered if the supply scenarios are to be closely approximated. Such detail is unwarranted in the scenariettes, as evidenced in Figures 9, 10, D.1, and D.3. However, in the sensitivity analysis presented in Appendix E, the specific structure of the electricity supply system is considered in detail.

Once again, the scenariette results are presented in two formats in Table C.4. The cumulative data are plotted as curves in Figures 8 and 9 of the text.

For direct comparison with the scenariette, the scenario results are taken from Figure C.8 and presented in the same format in Table C.5. These data are plotted as points in Figure 9 of the text.

C.3. District Heat

For the sake of completeness, scenariettes for the district heat supply system in region III are compared with the scenario results in Figure C.9.



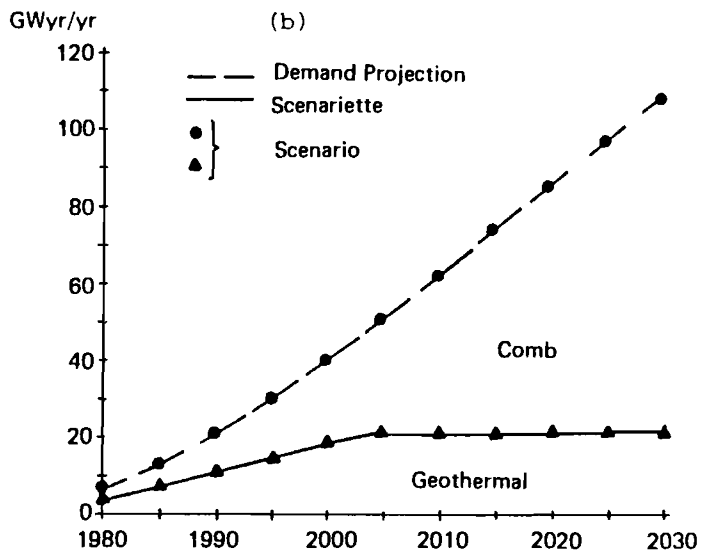


FIGURE C.9 Comparison of scenariette and scenario results for district heat supply system — region III (a) high, (b) low.

APPENDIX D: SCENARIETTES FOR OTHER REGIONS

This Appendix summarizes the major results for the high scenariettes in regions I (USA and Canada) and V (Africa, South and Southeast Asia). These scenariettes were obtained in the exact same manner as those described in Appendices B and C; therefore only the results are presented here (in graphical form).

The figures are self-explanatory. Note that the results for region I in Figures D.1 and D.2 look very much like those for region III. Meanwhile, the dynamics are rather different in region V; but the scenarios still adhere to the scenariettes in the secondary energy supply systems (Figures D.3 and D.4). The final figure (D.5) is an example in which the assumed constraints are not binding, but the dynamics of the scenariette and scenario are still qualitatively the same.

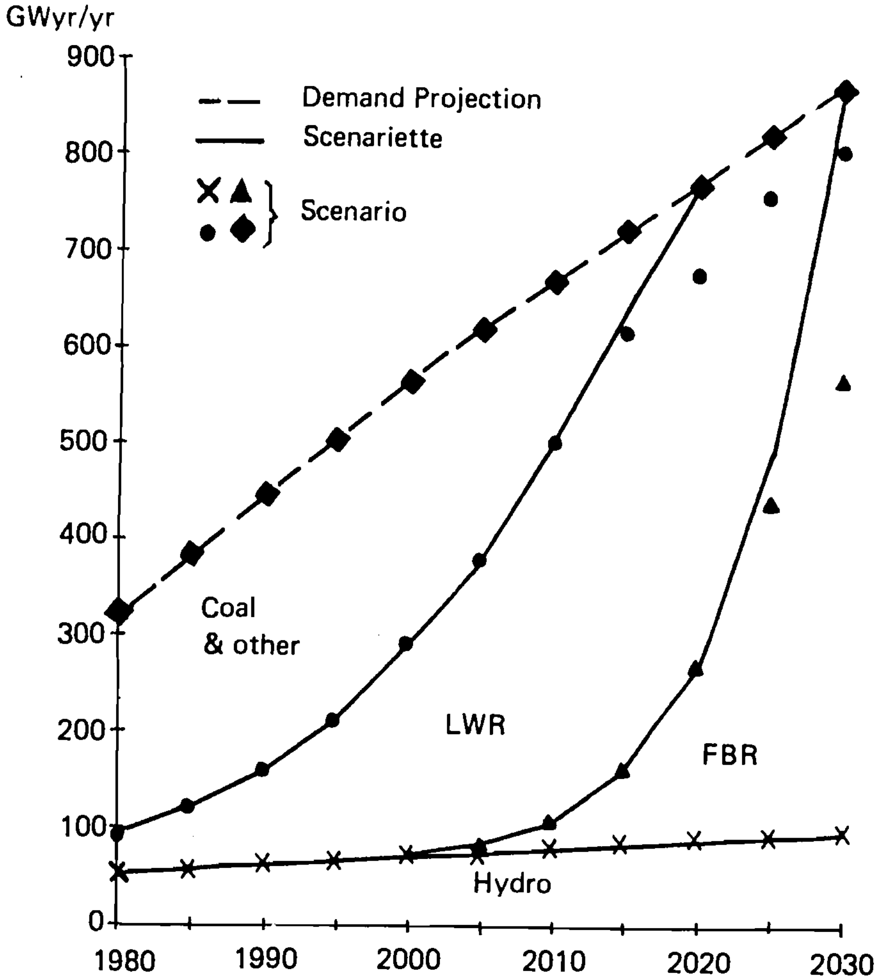


FIGURE D.1 Comparison of scenariette and scenario results for electricity generation in the USA and Canada (region I high).

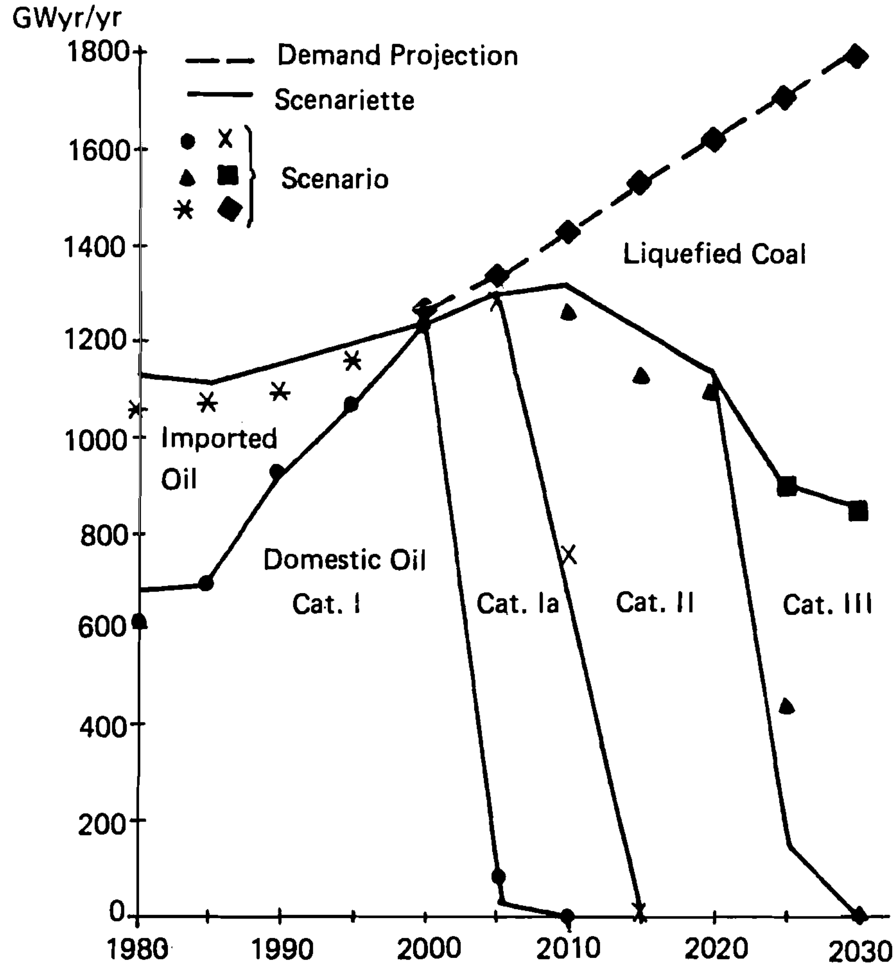


FIGURE D.2 Comparison of scenariette and scenario results for liquid fuel supply in the USA and Canada (region I high, cf. EIFW Figure 17-11A, p.558).

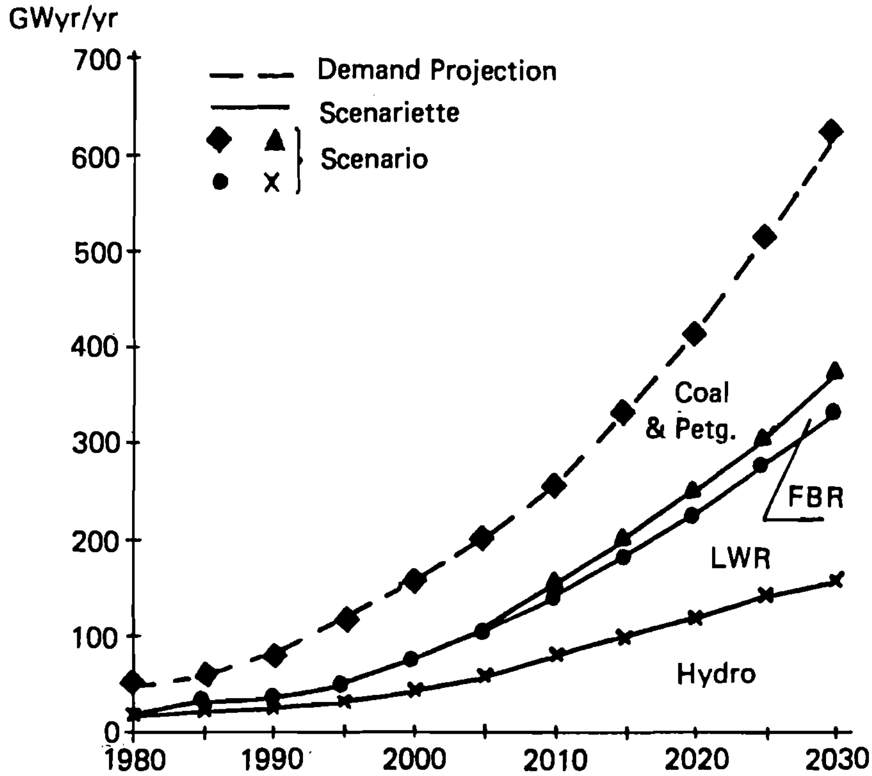


FIGURE D.3 Comparison of scenariette and scenario results for electricity generation – region V high (cf. EIFW Figure 17-16D, p.577).

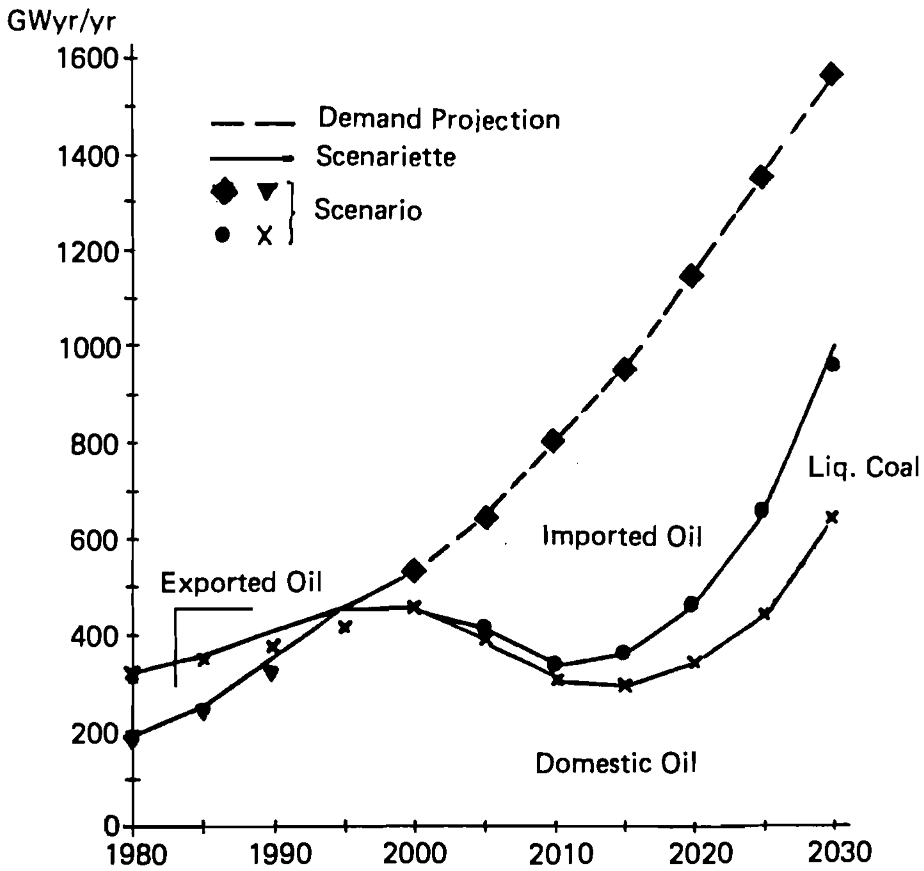


FIGURE D.4 Comparison of scenariette and scenario results for liquid fuel supply — region V high (cf. EIFW Figure 17-11I, p.562).

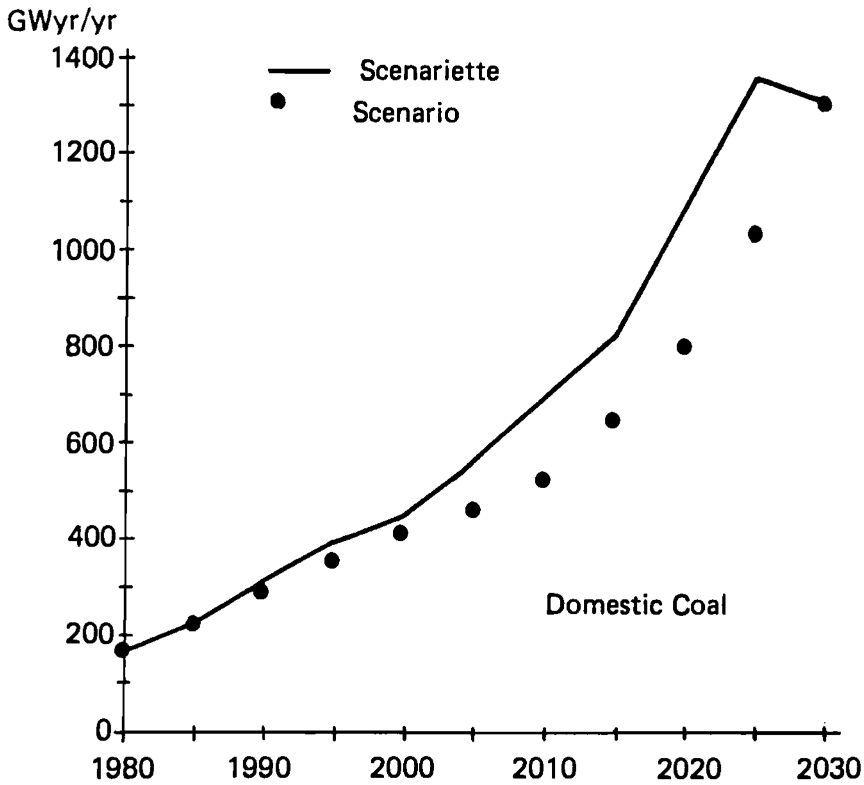


FIGURE D.5 Comparison of scenariette and scenario results for coal production — region V high.

APPENDIX E: SENSITIVITY ANALYSIS AND URANIUM SCENARIETTE

This Appendix contains the details concerning the uranium scenariettes, the sensitivity tests reported in Section 4, and the calculation of the rate of construction of new nuclear plants required by the scenarios. Unless otherwise stated, all of the input data and page numbers quoted in this Appendix come from the section in DOGR entitled "MESSAGE Input Data Listings for the High and Low Scenarios." The analyses in this Appendix are presented in great detail, so that the reader can reproduce the results. If the reader carries out the actual calculations described here, he or she will occasionally observe small discrepancies in the last decimal place from the figures shown in the tables. These discrepancies are simply due to rounding.

E.1. Uranium Scenariette — Region III

The uranium consumption scenariettes are unfolded from the scenariettes for electricity generated from light water reactors (LWRs), accounting for inventory requirements of LWR plants. The data in the next paragraph are taken from DOGR (p.100).

Each GW of installed LWR capacity requires an inventory of 500 metric tons (t) of U_3O_8. This inventory must be supplied at the beginning of the service life of the plant, and it is recovered (for possible further use) when the plant is decommissioned 30 years later (i.e. six 5-year time periods). In addition, each GWyr of electricity generated consumes 180 t of U_3O_8 as fuel. In the scenariette it is assumed that all LWR plants operate at the maximal plant capacity factor of 70%. (In the scenarios, there is considerable underutilization of LWR after the FBR is introduced, resulting in plant capacity factors considerably less than 70%.) The scenariette developed here is for region III (high).

We begin by accounting for the historical LWR installations. To approximate the age structure of the capacity existing in 1975, a constant annual growth was assumed (by the IIASA team) for the pre-1975 annual additions to capacity (DOGR, pp.8-9). Thus, only two input parameters were required to define the initial conditions of the 1975 capacity (namely, the installed capacity in 1975, and the historical growth rate). For region III, these parameters had the values 28.00 GW and 1.25, respectively. The equation for the annual additions to capacity in 1975 (Y_0) has the form (DOGR, p.29):

$$Y_0 = c_0 \frac{r^{-5} - 1}{5(r^{-30} - 1)} \tag{E.1a}$$

where

r = growth rate (1.25 in this case)

c_0 = 1975 capacity (28.00 GW in this case)

This gives $Y_0 = 3.770$ GW/yr. The remaining historical values of annual additions to capacity (Y_t) are computed from the following (DOGR, p.29):

$$Y_t = Y_0 r^{5t} \quad \text{for } t = -1, -2, \ldots, -5 \tag{E.1b}$$

Using notation similar to that in DOGR, the subscript t is used throughout this Appendix to denote five-year time intervals, where $t = 0$ corresponds to 1975, $t = 1$ is 1980, $t = 2$ is 1985, etc. Thus the scenarios run from $t = 1$ (1980) to $t = 11$ (2030). The above equations produce column (1) in Table E.1.

TABLE E.1 Assumed historical LWR capacity in region III.

	t	(1) Annual Buildup of Capacity Y_t (GW)	(2) New Additions to Capacity (GW)	(3) Year in which new additions are retired
1975	0	3.770	18.85	2005
1970	-1	1.235	6.18	2000
1965	-2	0.405	2.03	1995
1960	-3	0.133	0.67	1990
1955	-4	0.043	0.22	1985
1950	-5	0.014	0.07	1980

Since Y_t are *annual* additions, we may compute the total capacity that is newly added in each time period by simply multiplying Y_t by 5. This produces column (2) in Table E.2, and column (3) simply indicates the time period during which these new additions will be retired.

Now, the scenariette for electricity generated from LWR is copied into column (1) of Table E.2 (taken from column (2) of Table C.4 in Appendix C). Assuming a constant plant capacity factor of 0.7, we compute the net increased LWR capacity as a function of time. For example, the net annual capacity added between 1995 and 2000 is (1/5) (212−142)/0.7 = 20.00 GW/yr. This produces the "Net annual capacity added" figures shown in Table E.2, column (2). Continuing the example of the year 2000, note that 1.24 GW/yr are retired annually (this is the same 1.24 GW/yr that is assumed to have been installed 30 years earlier, in 1970; see column (1) of Table E.1). Thus, in order to achieve a net increase of 20 GW/yr, it is necessary to install a total of 21.24 GW/yr by 2000. This is the figure that appears in the "Annual buildup of capacity" column (4). The other figures in column (4) are generated in the same fashion. Column (3), labeled "Retired capacity", is generated simultaneously. Whenever a numerical figure is entered into column (4), the exact same figure is also entered into column (3) six time periods later. Thus the retired-capacity column is simply the annual buildup column shifted vertically downwards by 30 years. The first six figures in column (3) are copied (in reverse order) from column (1) of Table E.2.

We now use these data to compute the uranium extraction scenariette shown in Table E.2. This simply amounts to accounting for the uranium consumed as fuel in electricity generation; and the uranium required by or recovered from power plant inventories. For example, in the year 2000, the calculation has the form

$$(212\ \mathrm{GWyr/yr})\ (180\ \mathrm{t/GWyr}) + (21.24 - 1.24)\mathrm{GW/yr}(500\ \mathrm{t/GW}) = 48.16\ \mathrm{kt/yr} \qquad \text{(E.2)}$$

where

212 GWyr/ yr =	annual electricity generated from LWR scenariette
180 t/ GWyr =	uranium consumption (from DOGR, p.100)
21.24 GW/ yr =	annual buildup of capacity
1.24 GW/ yr =	annual retired capacity
500 t/ GW =	uranium inventory (from DOGR, p.100)

Finally, we keep track of the cumulative quantity of uranium extracted in column (6) of Table E.2. The input data specify 0.920 megatons (Mt) of cheap uranium for region III. When this is exhausted, the "LWR-step" occurs, as described in the text. In Table E.2, this happens in 2005 (when the cumulative uranium extracted reaches 0.938 > 0.920 Mt), which coincides with the LWR-step for the scenario shown in Figure 13 of the text. The figures in column (5) of Table E.2 are the uranium scenariette plotted in Figure 7 of the text.* Note that the only information used to generate these numbers was the LWR electricity scenariette, and the assumed LWR history summarized in Table E.1. For direct comparison with the scenario itself, Figure E.1 is a copy of the com-

*The proration of uranium extraction into categories 1 and 2 is handled in the same manner as for the fossil fuels (see Appendix B).

TABLE E.2. Scenariette for uranium extraction — region III high.

Year	(1) Annual electricity generation from LWR scenariette (GWyr/yr)	(2) Net annual capacity added (GW/yr)	(3) Retired capacity (GW/yr)	(4) Annual buildup of capacity (GW/yr)	(5) Uranium extraction scenariette (kt/yr)	(6) Cumulative uranium extracted (Mt)
1980	33	3.82	0.01	3.83	7.85	0.039
1985	55	6.28	0.04	6.32	13.04	0.104
1990	90	10.00	0.13	10.13	21.21	0.210
1995	142	14.86	0.41	15.27	32.99	0.375
2000	212	20.00	1.24	21.24	48.16	0.616
2005	293	23.14	3.77	26.91	64.31	0.938
2010	385	26.28	3.83	30.11	82.44	1.350
2015	455	20.00	6.32	26.32	91.90	1.809
2020	412	–	10.13	0.00	69.10	2.155
2025	55	–	15.27	0.00	2.27	2.166
2030	0	–	21.24	0.00	0.00	2.166

R3 REF W3H HI
NATURAL URANIUM
EXTRACTION

1980	7.97123	0.00000
1985	13.11545	0.00000
1990	21.17189	0.00000
1995	33.36409	0.00000
2000	48.66368	0.00000
2005	59.71366	6.43084
2010	0.00000	82.55410
2015	0.00000	86.03558
2020	0.00000	59.44938
2025	0.00000	41.11868
2030	0.00000	21.22472

	CURVE 1 + URAN 1	CURVE 2 X URAN 2
1980	7.97123	7.97123
1985	13.11545	13.11545
1990	21.17189	21.17189
1995	33.36409	33.36409
2000	48.66368	48.66368
2005	59.71366	66.14450
2010	0.00000	82.55410
2015	0.00000	86.03558
2020	0.00000	59.44938
2025	0.00000	41.11868
2030	0.00000	21.22472

FIGURE E.1 Natural uranium extraction in the IIASA scenarios — region III high. These data are plotted as points in Figure 7 of the text.

puter printout for the IIASA high scenario for uranium extraction in region III. The exhaustion of cheap uranium is exhibited in this figure by the zeros in the first column after 2005.

E.2. Introduction to the Sensitivity Tests

LWR-step. To compute the magnitude of the LWR-step (which is the same in all scenarios), recall from Table 1 of the text that the initial cost of LWR is \$136/kWyr, which is obtained from the following expression (EIFW, p.528)

$$C = \frac{[cap + inv \cdot rc] \cdot af}{pf} + cur + fc \cdot rc \tag{E.3}$$

where

C ≡ the cost of generating one kWyr of electricity.

cap ≡ capital cost (\$700/kW for LWR; see Table 1 of text)

inv ≡ uranium inventory requirement (for LWR only; 0.5 kg/kW)

rc ≡ resource cost

cur ≡ current costs (\$50/kWyr for LWR; see Table 1 of text)

fc ≡ fuel consumption (0.180 kg U_3O_8/kWyr for LWR)

af ≡ annualization factor (EIFW, p.528), which is given by

$$af \equiv \frac{\beta^5 - 1}{(5\ \text{yr})(\beta^{30} - 1)\beta^{2.5}} \tag{E.4}$$

(where the discount factor $\beta = 1/1.06$)

$= 0.070803/\text{yr}$.

pf ≡ plant load factor (this has a maximum value of 0.7 in the base load region)

Using the indicated parameter values for LWR, Equation (E.3) simplifies to

$$C = \$120.8/\text{kWyr} + (0.2306\ \text{kg/kWyr})(rc)$$

The cost of uranium in all scenarios is \$66/kg for category I and \$110/kg for category II (DOGR, p.37). Setting rc to these values in the above expression, we obtain

$$C = \begin{cases} \$136.02/\text{kWyr} & \text{if } rc = \$66/\text{kg (category I)} \\ \$146.17/\text{kWyr} & \text{if } rc = \$110/\text{kg (category II)} \end{cases}$$

Thus, the magnitude of the step in the LWR cost projection is \$146.17 − \$136.02 = \$10.15. These numbers round off to the figures discussed in the text (\$136, \$146, and \$10). The cost advantage of FBR over LWR is \$(146−143)/\$143 = 2.10%, as mentioned in the text.

In the sensitivity tests reported in this Appendix, the original IIASA scenario will be denoted by IS, and the alternative scenario which incorporates modified assumptions will be denoted by AS. There are three separate sensitivity tests described here, which are denoted by the subscripts 1, 2, and 3. The purpose of these analyses is to demonstrate that small perturbations in the various assumed parameters can produce scenarios that are significantly or drastically different from the IIASA scenarios. The general approach will be to select a particular portion of the original scenario (IS), and explore how this portion is altered (AS) under different assumed input data. In each case, the contributions to the objective function are computed for both IS and AS, in order to show that AS would be favored by the model. AS is not intended to be an exact specification of the optimal solution that the model would produce; rather it is a feasible solution that is close to optimal. It is expected that the model would yield only minor improvements to AS. The term "model" here refers to the energy supply model MESSAGE, which is a linear programming (LP) model. The sensitivity analyses presented here exemplify well known difficulties characteristic of single-objective LP models.

REGION VII: Demand

Table 1. Energy demand sectors, general description.

Name	Electricity	Liquid Fuels	Solid Fuels	Gaseous Fuels	Soft Solar	District Heat
Number of demand sectors	3	1	1	1	1	1
Fractions of year for each sector	.184 .384 .432	1	1	1	1	1
Fractions of demand attributed to each sector	.259 .438 .303	1	1	1	1	1

FIGURE E.2 Demand sector data used in the IIASA scenarios (from DOGR, p.82).

The sensitivity analyses presented here are concerned with the electricity supply system, since this system is the most carefully modeled in MESSAGE. Before presenting the details of the analyses, it is necessary to understand the structure of this system in the model. The demand for electricity is broken down into three load sectors in order to model diurnal and seasonal variations in demand. In all scenarios, the data defining these load sectors is as shown in Figure E.2 (reproduced from DOGR, p.12). These data determine the partition of the annual electricity consumption into standard load regions (called base, intermediate, and peak), as shown in Figure E.3. In this figure, the power index for a given load region is defined as the ratio of the fraction of demand to the net duration of that sector. For example, the peak load region has a power index of 0.259/0.184 = 1.408. The difference in power indices multiplied by the total duration gives the fraction of demand allocated to a given load region. For example, in the intermediate load region (1.141 − 0.701)(0.184 + 0.384) = 0.25. Thus, the intermediate load region accounts for 25% of the total annual electricity demand. Similarly, the base and peak load regions account for 70.1% and 4.9% of the demand, respectively.

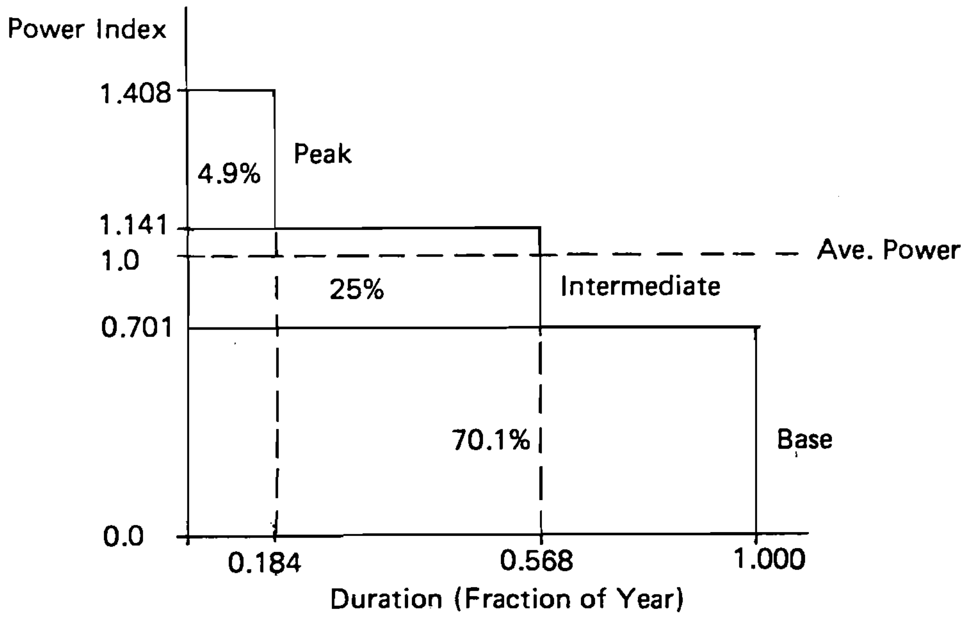


FIGURE E.3 Load regions for electricity demand in the IIASA scenarios.

In the development of scenariettes, the partition of electricity into load regions was not accounted for because it does not have a major effect on macroscopic trends in the supply system. The scenariettes were, in fact, concerned primarily with the base load region*. However, in the sensitivity analyses that follow, the load regions are important for two reasons. First, the model contains constraints on capacity (DOGR, pp.3,10), and it is necessary to satisfy all the constraints in the model when performing sensitivity analysis. For example, there must be sufficient installed capacity to be able to provide peak power, even though much of this capacity will be underutilized or idle during periods of intermediate and base load. The other reason for carefully considering the load regions is that the relative cost structure of the various technologies is different in each load region. The model's cost ranking by load regions is shown in Table E.3 for several technologies, arranged in order of

*An exception is hydropower, which is constrained to the peak and intermediate load regions in the scenarios for regions I, III, and VI (DOGR, p.96).

increasing cost. These technologies all have plant service lives of 30 years, and maximum plant capacity factors of 70% (by assumption). To see how these figures are generated, consider the gas turbine (GT) technology. As shown in Table 1 of the text, the capital and current costs are $170 and $17, respectively. In addition, the fuel consumption is 3.33 kW/yr gas per kWyr electricity produced (DOGR, p.96), and the cost of category I gas is $62/kWyr (DOGR, p.13). The annualization factor has the same value as calculated above for LWR (Equation (E.4)), namely 0.070803. Thus the costs are obtained as follows. If the plant is operated in the base load region only, it is utilized continuously, so the load factor is the full plant capacity factor (0.7). Thus, the cost is given by

$$\frac{0.070803}{0.7}(170) + 17 + 3.33(62) = \$240.66/\,\mathrm{kWyr} \quad \text{(base load)}$$

TABLE E.3 Assumed cost ranking of various electricity supply technologies by load region. (All figures shown are 1975 US$ per kWyr of electricity produced)

	Base	Intermediate	Peak
Least expensive	LWR $136	ACT $189	GT $317
	FBR $143	LWR $192	GFS $362
	ACT $152	PCT $196	ACT $367
	PCT $154	FBR $214	PCT $401
	GFS $216	GFS $241	LWR $465
Most expensive	GT $241	GT $254	FBR $556

Abbreviations:
PCT -- present coal technology (with scrubber);
ACT -- advanced coal technology (fluidized bed);
LWR -- light water reactor;
FBR -- fast breeder reactor;
GFS -- gas-fired steam;
GT -- gas turbine.
These figures are rounded to the nearest dollar, and it is assumed the cheapest category of fuel is consumed.

On the other hand, if the plant is operated only in the peak load region, it is utilized only 18.4% of the year. In this case the load factor is (0.7)(0.184) = 0.129, and the electricity cost becomes

$$\frac{0.070803}{0.129}(170) + 17 + 3.33(62) = \$316.77/\text{kWyr} \quad \text{(peak load)}$$

Note that the high cost of this technology in the base load region ($241) makes it the least desirable in that region (of the technologies shown in Table E.3). However, in the peak load region, the situation is reversed, and GT is the optimal technology. The reason for this is as follows. This technology combines a low capital cost ($170/kW) with a high fuel cost (3.33 x $62 = $206.46/kWyr). Thus, if the plant is operated continuously (base load region), the fuel cost is the overriding factor. However, if the plant is left idle most of the time (peak load region), then the low capital cost makes it very attractive, even though fuel costs are high. For this reason, gas turbine (GT) and gas-fired steam (GFS) plants are used in the scenarios to supply peak power. In regions II and VI where very low cost gas is available ($30/kWyr), gas-fired power is also used in the base and intermediate load regions.

In the analysis presented below, special care is taken to ensure that the total installed capacity in AS is equal to or greater than that in IS. This guarantees that the capacity constraints will be satisfied. In addition, the total electricity generation is the same in both IS and AS. The actual allocation of electricity generation to the various technologies depends on the cost ranking of the technologies in the different load regions, as discussed above.

E.3. Sensitivity with Respect to Cheap Uranium — Region IV

In the text, it was mentioned that only 1.6% of the total uranium available in region IV is allocated to the cheaper cost category. From DOGR (p.48), we obtain the specific input assumptions on uranium availability and allocation: 65 kt in the cheaper category (I), and 4.110 Mt in the expensive category (II). Thus, a total of 4.175 Mt of uranium is assumed to be available, of which 65 kt/4.175 Mt = 1.56% is allocated to the cheaper cost category. Figure E.4 is reproduced from the computer printout for uranium extraction in the low scenario. As seen in the figure, the cheap uranium is exhausted in 2005 (producing the LWR-step at that time).

Rerun Region 4 low
NATURAL URANIUM
EXTRACTION

units: kt/yr

1980	0.56	0.
1985	1.36	0.
1990	2.57	0.
1995	2.53	0.
2000	3.01	0.
2005	2.97	0.72
2010	0.	4.20
2015	0.	3.66
2020	0.	6.73
2025	0.	8.76
2030	0.	7.37

	+ uran 1	x uran 2
1980	0.56	0.56
1985	1.36	1.36
1990	2.57	2.57
1995	2.53	2.53
2000	3.01	3.01
2005	2.97	3.69
2010	0.	4.20
2015	0.	3.66
2020	0.	6.73
2025	0.	8.76
2030	0.	7.37

FIGURE E.4 Natural uranium extraction in the IIASA scenarios — region IV low.

The calculation carried out here is for the low scenario. In this example, it is shown that if the fraction of uranium allocated to the cheaper cost category is increased by just a few percent (from 1.6% to 8.7%), then the cheap uranium is not exhausted during the time horizon. The result is that the model chooses only hydropower, LWR, and some PCT for base load electricity, so that FBR is excluded altogether from the scenario. The conclusion is that the role of FBR in the scenario (i.e. the model's output) is very sensitive to the fraction of uranium allocated to the cheaper cost category (which is an arbitrary decision made by the user).

In this example, IS_1 refers to the total contribution to electricity generation and installed capacity from the three technologies LWR, FBR, and PCT (present coal technology) in the original IIASA scenario. In AS_1, this same contribution is fulfilled using only LWR and PCT. In particular, this means that after 1990 the base load electricity in AS_1 is supplied by hydropower and LWR only. FBR becomes an available option in the year 2005, but since the LWR-step does not occur, FBR is not used in base load.

In general, for most scenarios FBR is not competitive in the intermediate and peak load regions, as long as there is sufficient coal- and gas-fired power available (see Table E.3). In addition, if the assumed quantity of cheap uranium is small (so that the total contribution from "cheap-LWR" is limited), the strategy of cost minimization dictates that the entire cheap-LWR contribution be allocated to the base load region (rather than the intermediate load region). This holds because once the limit on cheap-LWR is reached, the increase in the marginal cost of electricity production is greater in the base load region (143–136 = 7[$/kWyr]) than in the intermediate load region (196–192 = 4[$/kWyr]). Thus the model "saves" more by installing cheap-LWR in the base load rather than the intermediate load region. It follows from these observations that in most applications of the model (not just this case), FBR is used only for base load power, and then only if the base load demand cannot be supplied by current installed capacity plus new additions to hydropower and/or cheap-LWR capacity*.

To satisfy the model's capacity constraints, the sum of installed LWR and PCT capacity in AS_1 is always greater than or equal to the sum of installed LWR,

*In all three sensitivity examples presented in this Appendix, FBR does not make a contribution, thus the balance equations for man-made materials (plutonium) are automatically satisfied (DOGR, p.6).

FBR and PCT capacity in IS_1.

We begin the computation by calculating the base load demand in the scenario. This amounts to simply multiplying the electricity demand projection given in DOGR (p.47) by 70.1%. This produces column (1) in Table E.4. Since hydropower is by far the cheapest electricity source, the model delegates all of the available hydropower to the base load region. This maximal contribution from hydropower is shown in Figure E.5, which is reproduced from the computer printout for electricity generation in the scenario. Subtracting this contribution from the base load demand, we obtain the residual base load demand shown in column (2) of Table E.4. To compute the minimum installed LWR capacity required to supply this residual, we divide the numbers in column (2) by the base load factor, which (because of continuous utilization in the base load region) is the maximum plant capacity factor (0.703)*. The result of this computation is shown in column (3) of Table E.4.

Before proceeding further, it is necessary to reduce this increased level of LWR capacity if it exceeds the constraint on the maximum possible installed LWR capacity. This constraint, shown in column (4) of Table E.4, is determined by taking the composite of the LWR supply constraint and the constraint on total nuclear energy (DOGR, p.50). Each numerical entry in column (4) is chosen to be the more restrictive of these two constraints. The first three numbers in column (3) are indeed limited by the corresponding values in column (4), and the resulting gap will be filled with coal (as it is in IS_1). After 1990, the numbers shown in column (3) satisfy the constraints specified in column (4).

*The precise input values for the maximum plant capacity factor for LWR, FBR, PCT and ACT vary slightly from one scenario to the next. The range is from 0.700 to 0.703 or more, so the effect is negligible. Nevertheless, I have tried to be consistent with each individual scenario.

Rerun Region 4 low
ELECTRICITY GENERATION
BY TECHNOLOGY

units: GWel

	+ lwr	x c-lwr	a fbr	> coal	v c-coal	< advcoa	+ hydro	x solar	a petg
1980	2.07	0.	0.	5.09	0.	0.	21.61	0.	10.24
1985	5.58	0.	0.	9.34	0.	0.	27.81	0.	8.27
1990	11.19	0.	0.	14.53	0.	0.	34.23	0.	6.26
1995	13.33	0.	0.	22.38	0.	0.	42.55	0.	3.93
2000	15.86	0.	0.	29.84	0.	0.26	52.78	0.	2.67
2005	19.15	0.	1.40	32.45	0.	0.88	64.34	0.	4.39
2010	20.67	0.	4.48	35.60	0.	4.86	77.23	0.	6.16
2015	15.81	0.	9.58	43.57	0.	11.82	90.87	0.	8.75
2020	31.67	0.	17.09	33.54	0.	20.52	104.99	0.	11.39
2025	41.48	0.	27.51	25.49	0.	33.50	119.56	0.	16.65
2030	43.12	0.	41.41	14.57	0.	51.68	131.49	0.	30.13
	$\hat{X} = 35.915$		$\hat{X} = 7.141$	$\hat{X} = 55.460$					

	+ lwr	x c-lwr	a fbr	> coal	v c-coal	< advcoa	+ hydro	x solar	a petg
1980	2.07	2.07	2.07	7.15	7.15	7.15	28.76	28.76	39.00
1985	5.58	5.58	5.58	14.91	14.91	14.91	42.73	42.73	51.00
1990	11.19	11.19	11.19	25.72	25.72	25.72	59.94	59.94	66.20
1995	13.33	13.33	13.33	35.72	35.72	35.72	78.27	78.27	82.20
2000	15.86	15.86	15.86	45.70	45.70	45.96	98.73	98.73	101.40
2005	19.15	19.15	20.55	53.00	53.00	53.87	118.21	118.21	122.60
2010	20.67	20.67	25.15	60.75	60.75	65.61	142.84	142.84	149.00
2015	15.81	15.81	25.38	68.95	68.95	80.77	171.65	171.65	180.40
2020	31.67	31.67	48.76	82.30	82.30	102.82	207.81	207.81	219.20
2025	41.48	41.48	68.99	94.48	94.48	127.99	247.55	247.55	264.20
2030	43.12	43.12	84.54	99.10	99.10	150.78	282.27	282.27	312.40

FIGURE E.5 Electricity generation by technology in the IIASA scenarios — region IV low.

Continuing the calculation, we now seek to establish the annual buildup of LWR capacity that is required to meet the minimum installation specified in column (3). In so doing, it is necessary to satisfy rigorously each constraint in the model, while at the same time accounting for retired LWR capacity. We begin with the historical LWR capacity, which turns out to be quite simple in this case. In DOGR (p.50), we find that the assumed 1975 LWR capacity is 0.44 GW, with an historical growth rate of 99%. This large historical growth rate results in an annual buildup of 0.085 GW/yr in 1975 and 0.003 GW/yr in 1970, and essentially zero for previous years. After 30 years, these installations are taken out of service (decommissioned), so the numbers 0.003 GW/yr and 0.085 GW/yr are entered in the "Annual retired capacity" (column (7)) of Table E.4 in 2000 and 2005, respectively. In addition, 0.085 GW/yr is entered as the first figure in the "Annual buildup of LWR capacity" (column (5)) of the table.

TABLE E.4. Installed LWR capacity in alternative scenario AS_1 — region IV low.

	(1) Base load demand (GWyr/yr)	(2) Residual base load demand (GWyr/yr)	(3) Minimum LWR capacity required (GW)	(4) Constraint on installed LWR capacity (GW)	(5) Annual buildup of LWR capacity (GW/yr)	(6) Constraint on annual buildup of LWR capacity (GW/yr)	(7) Annual retired LWR capacity (GW/yr)	(8) LWR capacity installed (GW)
1975	--	--	--	--	(0.085)			
1980	27.34	5.73	2.95	2.95	0.502	0.502	0.0	2.95
1985	35.75	7.94	7.96	7.96	1.002	1.002	0.0	7.96
1990	46.27	12.04	15.97	15.97	1.602	1.602	0.0	15.97
1995	57.48	14.93	21.32	28.00	1.070	2.322	0.0	21.32
2000	70.80	18.02	25.74	44.00	1.0322	1.684	0.003	26.47
2005	85.52	21.18	30.25	64.00	1.639	1.639	0.085	34.23
2010	103.75	26.52	37.87	89.00	2.366	2.366	0.502	43.56
2015	125.48	34.61	49.43	119.00	3.240	3.240	1.002	54.74
2020	152.12	47.13	67.31	151.00	4.288	4.288	1.602	68.17
2025	182.96	63.40	90.55	191.00	5.545	5.545	1.070	90.55
2030	215.91	84.42	120.56	240.00	7.034	7.054	1.0322	120.56
					$\hat{Y} = 4.352$			

In generating the remaining figures in column (5), a restrictive constraint must be satisfied: the constraint on annual buildup Y_t (during time period t), which has the form (DOGR, p.9)

$$Y_t \leq \gamma Y_{t-1} + g \qquad \text{(E.5)}$$

The assumed parameter values in this case are $\gamma = 1.20$ and $g = 0.40$ (DOGR p.50), and the initial condition is $Y_0 = 0.085$ (from the last paragraph). To achieve the minimum capacities specified in column (3), we begin by proceeding at the maximum permissible buildup rate. Thus $Y_1 = (1.2)(0.085) + 0.40 = 0.502$ as shown in columns (5) and (6). This results in a total of (0.502 GW)(5) = 2.51 GW new additions to capacity during the first time period, which makes for a total installed capacity of (0.44 + 2.51) GW = 2.95 GW by 1980, as shown in column (8). This agrees with the required minimum specified in column (3). Continuing in the same fashion, the columns develop as shown, up to 1995. At this point, the constraint on annual buildup is 2.322 GW (column (6)), but to implement this much buildup would produce more capacity than is needed, so the buildup is set at 1.070, which gives 5(1.070) + 15.97 = 21.32 GW, as shown in columns (9) and (3).

To obtain the minimum required installed capacity of 25.74 GW in the year 2000, the annual buildup in 2000 should be set to 0.887 GW. However, if this value is selected, then the subsequent annual buildup constraints are sufficiently restrictive that it is not possible to meet the minimum required LWR capacity figure of 90.55 GW by 2025 (see column (3)). Thus a value greater than 0.887 GW must be chosen. This means that more LWR capacity will be installed than is actually required, but this creates no difficulties -- it simply reduces the amount of PCT to be installed. Although we are free to choose any value for the annual buildup that does not exceed the constraining value (1.684 shown in column (6)), it is desirable to choose this number as small as possible to minimize the amount of LWR capacity that is installed in excess of the minimum required shown in column (3). By trial and error, the value 1.0322 is found to be appropriate (column (5)), because it leads to exactly 90.55 GW installed capacity by 2025 (column (8)).

Between 2000 and 2025, we proceed at the new set of maximum annual buildup rates (column (6)) that are generated from the choice of 1.0322 in column (5). Note that this constraint is updated in each time period, depending on the annual buildup during the previous time period. For example, in 2020, the constraint is computed from Equation (E.5) as follows: (1.2)(3.240) + 0.4 = 4.288, as shown in column (6). In the final time period, the buildup constraint is not binding, and the value 7.034 is selected in order to reach a final installed capacity of 120.56 GW (column (8)).

In generating the annual buildup rates shown in column (5), the retired LWR capacity has been taken into account. New additions to capacity are retired after 30 years of service, and thus the retired capacity column (7) is equivalent to column (5), but shifted vertically downward by six time periods. From these two columns, the net installed capacity is determined. For example, in 2020, the calculation is

$$5\,(4.288 - 1.602)\ \text{GW} + 54.74\ \text{GW} = 68.17\ \text{GW}\ .$$

The next step in developing AS_1 is to specify the installed coal (PCT) capacity. As discussed earlier, the total installed capacity in AS_1 must be at least as much as in IS_1. Since LWR and PCT (in AS_1) are used in place of LWR, FBR and PCT in IS_1, the required installed capacity is the circled column in Figure E.6 (which is reproduced from the computer printout for IS_1). These data are copied into column (1) of Table E.5. We subtract from this the installed LWR capacity for AS_1 calculated above (column (8) of Table E.4). This yields the minimum required installed PCT capacity shown in column (2) of Table E.5. Up until 2015 there is less PCT in AS_1 than in IS_1 (see Table E.10), so the constraint on total PCT installed capacity is automatically satisfied. After 2015, the installed PCT capacity in AS_1 is somewhat greater than that in IS_1, but this is well within the total installed capacity constraint (see DOGR, p. 53).

The initial conditions for PCT in both IS_1 and AS_1 are 3.00 GW installed and r = 1.12 (growth rate parameter). This yields the age structure for PCT (calculated from Equation (E.1)), as shown in Table E.6. The figures in the first column of this table are then transferred in reverse order to the "Retired capacity" column (5) of Table E.5.

In developing the annual buildup rates for PCT, it is again important that we always remain within the constraints on buildup rates. The annual buildup

Rerun Region 4 low
ELECTRICITY
INSTALLED CAPACITY

units: GWel

1980	2.95	0.	0.	8.80	0.	0.	24.57	0.	36.75
1985	7.96	0.	0.	20.88	0.	0.	31.63	0.	33.95
1990	15.97	0.	0.	35.58	0.	0.	38.92	0.	32.23
1995	19.04	0.	0.	54.50	0.	0.	48.38	0.	30.52
2000	22.64	0.	0.	83.31	0.	2.00	60.01	0.	30.80
2005	27.34	0.	2.00	84.63	0.	6.80	73.16	0.	34.06
2010	32.97	0.	6.40	84.48	0.	15.51	87.82	0.	47.82
2015	39.73	0.	13.67	82.28	0.	29.71	103.34	0.	64.61
2020	47.84	0.	24.40	83.36	0.	51.59	119.38	0.	80.25
2025	65.19	0.	39.28	64.08	0.	84.22	135.96	0.	106.00
2030	61.57	0.	59.13	36.62	0.	129.91	149.52	0.	144.05

	+ lwr	x c-lwr	a fbr	> coala	v c-coal	< advcoa	+ hydro	x solar	a petg
1980	2.95	2.95	2.95	11.75	11.75	11.75	36.32	36.32	73.07
1985	7.96	7.96	7.96	28.84	28.84	28.84	60.47	60.47	94.42
1990	15.97	15.97	15.97	51.55	51.55	51.55	90.47	90.47	122.70
1995	19.04	19.04	19.04	73.54	73.54	73.54	121.92	121.92	152.44
2000	22.64	22.64	22.64	105.95	105.95	107.95	167.97	167.97	193.76
2005	27.34	27.34	29.34	113.97	113.97	120.76	193.93	193.93	227.99
2010	32.97	32.97	39.37	123.85	123.85	139.36	227.18	227.18	275.00
2015	39.73	39.73	53.40	135.68	135.68	165.39	268.73	268.73	333.34
2020	47.84	47.84	72.25	155.61	155.61	207.20	326.59	326.59	406.84
2025	65.19	65.19	104.47	168.56	168.56	252.78	388.74	388.74	494.74
2030	61.57	61.57	120.70	157.32	157.32	287.23	436.75	436.75	580.80

FIGURE E.6 Electricity installed capacity in the IIASA scenarios — region IV low.

TABLE E.5 Installed PCT capacity in alternative scenario (AS_1) — region IV low.

	(1) Installed Capacity from IS_1 (GW)	(2) Minimum PCT Capacity Required (GW)	(3) Annual Buildup of PCT Capacity (GW/yr)	(4) Constraint on annual buildup of PCT Capacity (GW/yr)	(5) Annual Retired PCT Capacity (GW/yr)	(6) PCT Capacity Installed (GW)
1975	(3.00)					
1980	11.75	8.80	1.176	1.176	0.016	8.80
1985	28.84	20.88	2.444	2.444	0.028	20.88
1990	51.55	35.58	2.989	2.989	0.049	35.58
1995	73.54	52.22	3.414	3.870	0.086	52.22
2000	105.95	79.47	5.602	5.914	0.152	79.47
2005	113.97	79.74	0.7558	8.243	0.269	81.90
2010	123.85	80.29	1.458	1.458	1.176	83.31
2015	135.68	80.94	2.441	2.441	2.444	83.30
2020	155.61	87.44	3.818	3.818	2.990	87.44
2025	168.56	78.01	1.526	5.746	3.414	78.01
2030	157.32	36.76	0.00	2.536	5.602	50.00
			$\hat{Y} = 8.667$			

TABLE E.6 Age structure of PCT in region IV.

	Annual Buildup of Capacity (GW/yr)	Retires in
1975	0.269	2005
1970	0.152	2000
1965	0.086	1995
1960	0.049	1990
1955	0.028	1985
1950	0.016	1980

rates in IS_1 do not satisfy the inequality (E.5) until after the year 2000; therefore we shall use the IS_1 buildup rates themselves as constraints in AS_1, after which we again use (E.5) to generate the constraints (with $\gamma = 1.40$ and $g = 0.40$; DOGR, p.53). This procedure is well justified because the buildup of PCT is identical in both AS_1 and IS_1 up through 1990, after which it drops off in AS_1 relative to IS_1. The five constraints from IS_1 (1980 to 2000) are copied into column (4) of Table E.5 from column (4) of Table E.10 (to be discussed below).

We now develop the annual buildup rates. In the first time period, we have

$$Y_1 = \frac{(8.80 - 3.00)}{5} + 0.016 = 1.176$$

Since 1.176 does not exceed the constraint (which has the same value) it is an admissible value for Y_1. We continue in this fashion up through 2000. Between 2005 and 2020 trial and error is again used to determine the smallest buildup rate in 2005 that results in the correct installed capacity in 2020 (87.44 GW, see columns (2) and (6) of Table E.5). After 2020, the constraint on buildup rates is no longer binding. Columns (5) and (6) of Table E.5 are obtained in the same fashion as their counterparts for LWR in Table E.4.

TABLE E.7 Electricity generation and uranium extraction in AS_1 — region IV low.

Year	(1) Total electricity generation (GWyr/yr)	(2) LWR electricity generation (GWyr/yr)	(3) PCT electricity generation (GWyr/yr)	(4) Annual uranium extraction (kt/yr)	(5) Cumulative uranium extraction (kt)
1975	--				
1980	7.15	2.07	5.08	0.62	3.12
1985	14.91	5.57	9.34	1.50	10.64
1990	25.72	11.18	14.54	2.81	24.70
1995	35.72	14.93	20.79	3.22	40.82
2000	45.70	18.31	27.39	3.81	59.87
2005	53.00	22.76	30.24	4.87	84.24
2010	60.75	28.78	31.97	6.11	114.80
2015	68.95	36.72	32.23	7.73	153.44
2020	82.30	47.47	34.83	9.89	202.88
2025	94.48	63.40	31.08	13.65	271.13
2030	99.10	84.42	14.68	18.20	362.11
		$\hat{X} = 46.083$	$\hat{X} = 52.420$		8.67% of 4.175 Mt

The next step in developing AS_1 is to specify how the electricity generation is allocated. Since the total electricity generated must be the same in AS_1 and IS_1, we take the total electricity generated from LWR, FBR, and PCT in IS_1 to be the total for LWR and PCT in AS_1. This is shown in column (1) of Table E.7, which is copied directly from the computer printout for electricity generation in IS_1 (Figure E.5). Since LWR was installed for residual base load, it will be used to generate at least this amount of electricity (after 1990, see column (2) of Table E.4). However, slightly more LWR was installed than was required for base load, and slightly more PCT was installed than required. This was necessary in order to satisfy buildup and capacity constraints. Thus a choice must be made as to which technology is to be utilized to the fullest extent. Comparing the operating costs, we have (using data from DOGR, pp.94, 100)

LWR: \$50/kWyr + (0.18 kg/kWyr)(\$66/kg) = \$61.88/kWyr

PCT: \$23/kWyr + (2.79 kWyr/kWyr)(\$27/kWyr) = \$98.33/kWyr

Since LWR is cheaper to operate, the excess LWR capacity will be utilized in the intermediate load region. This gives the LWR electricity generation figures shown in column (2) of Table E.7. In those time periods (after 1990) for which there is no excess LWR capacity, the entry in column (2) is identical to the corresponding entry for residual base load demand in column (2) of Table E.4. For cases in which there is excess LWR capacity, the calculation of LWR electricity generation proceeds as follows: In the intermediate load region, the load factor is (0.7003)(0.184 + 0.384) = 0.398. Thus, taking the year 2015 as an example, the electricity generation is given by

$$34.61 + (54.74 - 49.43)(0.398) = 36.72$$

where

34.61 =	residual base demand (GWyr/yr)
(54.74–49.43) =	excess capacity (GW)
0.398 =	intermediate load factor

Finally, the PCT electricity generation (column (3) of Table E.7) is obtained by subtracting the LWR electricity generation (column (2)) from the total electricity generation (column (1)).

The last step in specifying AS_1 is to calculate the consumption of resources. Columns(4) and (5) of Table E.7 show the annual and cumulative uranium that would be extracted in AS_1. The calculations are performed in the same manner as above for region III (see Equation (E.2)), using the LWR electricity generation (column (2)) and annual buildup and retired capacity (columns (5) and (7) of Table E.4). For example, in 2025, the calculation of annual uranium extraction is

$$(63.40 \text{ GWyr/yr})(180 \text{ t/GWyr}) + (5.545 - 1.070) \text{ GW/yr}(500 \text{ t/GW})$$
$$= 13.65 \text{ kt/yr}$$

The cumulative uranium extraction is then determined from (13.65 kt/yr)(5 yr) + 202.88 kt = 271.13 kt. By 2030, the cumulative uranium extracted in AS_1 is 362.11 kt, which is 8.67% of 4.175 Mt available uranium (DOGR, p.48).

Although the total quantity of coal burned to generate electricity is considerably less in AS_1 than in IS_1, the temporal distribution of consumption is somewhat different. The mathematical formulation of the constraints (DOGR, p.9) does not permit resources to be extracted in one time period and then used in a later time period. In the final three time periods of AS_1, the requirements for coal exceed the assumed extraction constraints. Thus in order to permit the distribution of coal consumption in AS_1, the last three coal extraction constraints would need to be raised from 170, 180, 195 (DOGR, p.49) to 173.6, 195.6, 195.3, respectively. These new values are obtained as follows. Taking the year 2030 as an example, the PCT electricity generation is 14.68 GWyr/yr in AS_1 and 14.57 GWyr/yr in IS_1 (Figure E.5). Thus the constraint becomes 195 + (14.68−14.57)2.79 = 195.3.

E.4. Computation of the Objective Function.

To verify that AS_1 would indeed be favored over IS_1, we now compute the contributions to the objective function from both scenarios. The objective function in MESSAGE is the sum of separate contributions from each demand sector (electricity, liquid fuels, etc.). We consider here only the contribution from the electricity production sector. To treat this sector in isolation is valid because MESSAGE does not permit modification or rearrangement of the demand data. Thus, once the electricity demand is specified (in the form of time series inputs to MESSAGE), it can not be changed. In particular, no endogenous adjustments of demand are carried out to optimize basic economic trade-offs between, say, new supply installations and demand reductions or displacements (via efficiency improvements, conservation, substitution, etc.). Such adjustments are made informally at the discretion of the user (based perhaps on shadow prices). The cost data furnished to MMI are concerned with energy supply alternatives only.*

The objective function is the sum of current costs, capital costs, and fuel costs, discounted over time. The formulas used for these three terms are specified in the expressions (21), (22) and (23) in DOGR, respectively (section entitled "MESSAGE Model Description", p.15). For LWR and PCT, all three terms are nonzero, while for FBR, the fuel costs are assumed (by the IIASA analysts) to be zero.

In the following equation, we have summed over the demand load regions, since we are interested in the total cost of supplying electricity, and this does not depend on the distribution of the individual supply activities (X_t) into load regions (this holds because the objective function is linear in the supply activities). The total cost C of generating electricity from a particular technology is given by

$$C = \sum_{t=1}^{11} 5X_t \cdot cur \cdot \beta^{5t-2.5} + \sum_{t=1}^{11} 5(Y_t \cdot cap + Y_t \cdot inv \cdot rc)\beta^{5t-5}(1-V_t) + \sum_{t=1}^{11} 5R_t \cdot rc \cdot \beta^{5t-2.5} \tag{E.6}$$

where

X_t = electricity generated in time period t

cur = current costs. This parameter has the value \$50/kWyr (or

*Conservation and similar measures are often much more cost effective than new supply capacity, by as much as a factor of five (Foley and Nassim, 1981). In view of this, it is ironic that the scenarios are ostensibly based on cost optimization, because MMI does not systematically account for some of the most important cost factors. This is a serious deficiency; see Wynne (1983) for further discussion.

\$50 x 10^6/GWyr) for both LWR and FBR (DOGR, pp. 98,100)

β = discount factor = 1/1.06

5t−2.5 and 5t−5 are exponents

Y_t = annual additions to capacity in time period t

cap = capital costs; e.g. \$700/kW (or \$700 x 10^6/GW) for LWR; \$920/kW (or \$920 x 10^6/GW) for FBR (DOGR, pp. 98,100)

inv = uranium inventory required by LWR plants (500 t/GW). This must be annualized in the same manner as the capital cost (DOGR, p.37).

rc = resource cost. For cheap LWR, *rc* = \$66/kg (or \$66000/t). This figure is used for both IS and AS.

For FBR, *rc* = 0.

R_t = annual consumption of fuel in time period t for generating electricity.

V_t = terminal valuation factor (DOGR, p.15). This factor is a correction applied to the objective function so that the capital cost of capacity existing after 2030 is effectively excluded from the optimization. It has the form

$$V_t = \begin{cases} 0 & \text{for } t < 6 \\ \beta^{5(12-t)} & \text{for } t \geq 6 \end{cases}$$

To see its effect:

t	$(1-V_t)$
6	0.8259
7	0.7670
8	0.6882
9	0.5827
10	0.4416
11	0.2527

Combining the first and third terms in (E.6), the equation may be rewritten as

$$C = 5\sum_{t=1}^{11} X_t(cur + R_t \cdot rc)\beta^{5t-2.5} + 5\sum_{t=1}^{11} Y_t(cap + inv \cdot rc)\beta^{5t-5}(1-V_t)$$

Since $R_t = X_t \cdot fc$, where fc is the fuel consumption (per unit of electricity generated), this becomes

$$C = 5(cur + fc \cdot rc)\sum_{t=1}^{11} X_t\beta^{5t-2.5} + 5(cap + inv \cdot rc)\sum_{t=1}^{11} Y_t\beta^{5t-5}(1-V_t)$$

or

$$C = A\hat{X} + B\hat{Y} \tag{E.7}$$

where

$$A \equiv 5(cur + fc \cdot rc) \tag{E.8}$$

$$B \equiv 5(cap + inv \cdot rc) \tag{E.9}$$

$$\hat{X} \equiv \sum_{t=1}^{11} X_t\beta^{5t-2.5} \tag{E.10}$$

$$\hat{Y} \equiv \sum_{t=1}^{11} Y_t\beta^{5t-5}(1-V_t) \tag{E.11}$$

The values of the constants A and B are shown in Table E.8 for various technologies. The numerical values displayed in this Table for the parameters cap, cur, fc, rc, and inv are all taken directly from DOGR (pp.13,93,94,98,100). The resulting coefficients A and B are used in the calculation of the objective function. As an example, to calculate the contribution to the objective function from electricity generated by LWR, we have:

$$C_{LWR} = 0.3094\times10^9 \sum_{t=1}^{11} X_t\beta^{5t-2.5} + 3.6650\times10^9 \sum_{t=1}^{11} Y_t\beta^{5t-5}(1-V_t)$$

$$= 10^9(0.3094\ \hat{X}_{LWR} + 3.6650\ \hat{Y}_{LWR})$$

where

$$\hat{X}_{LWR} \equiv \sum_{t=1}^{11} X_{t,LWR}\beta^{5t-2.5}$$

and

TABLE E.8 Cost coefficients in the objective function for different technologies.

Parameter	LWR	FBR	PCT	ACT
cap (\$/GW)	700×10^6	920×10^6	550×10^6	480×10^6
cur (\$/GWyr)	50×10^6	50×10^6	23×10^6	36×10^6
fc (GWyr/GWyr[a])	180	--[c]	2.79	2.50
rc (\$/GWyr[b])	66000	0.0	27×10^6	27×10^6
inv (t/GW)	500	0.0	0.0	0.0
A (\$10^9/GWyr)	0.30940	0.25000	0.49165	0.51750
B (\$10^9/GW)	3.66500	4.60000	2.75000	2.40000

[a]in the case of LWR, the units are t/GWyr
[b]in all cases, the cheapest category of fuel is assumed. In the case of LWR, the units are \$/ton.
[c]since $rc = 0$ by assumption, *fc* plays no role in the objective function (see Equation (E.8))

$$\hat{Y}_{LWR} \equiv \sum_{t=1}^{11} Y_{t,LWR} \beta^{5t-5}(1-V_t) \ .$$

In order to compute the contributions to the objective function, it is first necessary to compute the weighted sums $\hat{X}$ and $\hat{Y}$ for each technology considered in each scenario. In all cases, $\hat{X}$ will be used to denote the weighted sum for electricity generation, and $\hat{Y}$ will denote the weighted sum for annual buildup of capacity. These were calculated for this work using a programmable hand calculator.

For AS_1, the weighted sum $\hat{X}$ has the value shown at the base of column (2) in Table E.7 for LWR. Similarly, $\hat{X}$ for PCT in AS_1 is shown at the base of column (3) of the table. The values for $\hat{Y}$ in AS_1 are shown in Tables E.4 and E.5 for LWR and PCT, respectively. All of these sums appear in Table E.11 for AS_1.

For the IIASA scenario (IS), the data for electricity generation (X_t) and installed capacity come directly from computer printouts for the scenario. For IS_1 these are shown in Figures E.5 and E.6, respectively. From the latter figure, the annual buildup of capacity Y_t is computed as shown in Table E.9 for LWR and FBR, and in Table E.10 for PCT. The logic is the same as in the calculations performed above. For example, in 2010, the calculation of annual LWR buildup is as follows. The net annual LWR buildup is given by

$$\frac{(32.97-27.34)\ \text{GW}}{5\ \text{yr}} = 1.126\ \text{GW/yr}$$

as shown in column (2) of Table E.9. Adding to this the retired LWR capacity (column (3)), we obtain the annual buildup

$$(1.126 + 0.502)\ \text{GW/yr} = 1.628\ \text{GW/yr}$$

as shown in column (4) of the table.

TABLE E.9 Annual buildup of nuclear capacity in IS_1 — region IV low.

	(1) Installed LWR Capacity (GW)	(2) Net annual LWR Buildup (GW/yr)	(3) Retired LWR Capacity (GW/yr)	(4) Annual LWR Buildup (GW/yr)	(5) Installed FBR Capacity (GW)	(6) Annual FBR Buildup (GW/yr)
1975	(0.44)	(0.085)		(0.085)		
1980	2.95	0.502	0	0.502	0	0
1985	7.96	1.002	0	1.002	0	0
1990	15.97	1.602	0	1.602	0	0
1995	19.04	0.614	0	0.614	0	0
2000	22.64	0.720	0.003	0.723	0	0
2005	27.34	0.940	0.085	1.025	2.00	0.400
2010	32.97	1.126	0.502	1.628	6.40	0.880
2015	39.73	1.352	1.002	2.354	13.67	1.454
2020	47.84	1.622	1.602	3.224	24.40	2.146
2025	65.19	3.470	0.614	4.084	39.28	2.976
2030	61.57	-0.724	0.723	0.000	59.13	3.970
				$\hat{Y} = 3.566$		$\hat{Y} = 0.596$

The sums $\hat{Y}$ in IS_1 are shown in Table E.9 for LWR and FBR, and in Table E.10 for PCT. Meanwhile, the sums $\hat{X}$ in IS_1 are obtained directly from the computer printout, as shown in Figure E.5.

The calculation of the contribution to the objective function is summarized in Table E.11. The values for the weighted sums $\hat{X}$ and $\hat{Y}$ are summarized in this table, and the contribution C to the objective function from each technology is calculated using Equation (E.7) and the values of the constants A

TABLE E.10 Annual buildup of PCT capacity in IS_1 — region IV low.

	(1) Installed Capacity (GW)	(2) Net annual Buildup (GW/yr)	(3) Annual Retired Capacity (GW/yr)	(4) Annual buildup (GW/yr)
1975	(3.00)			
1980	8.80	1.160	0.016	1.176
1985	20.88	2.416	0.028	2.444
1990	35.58	2.940	0.049	2.989
1995	54.50	3.784	0.086	3.870
2000	83.31	5.762	0.152	5.914
2005	84.63	0.264	0.269	0.533
2010	84.48	-0.030	1.176	1.146
2015	82.28	-0.440	2.444	2.004
2020	83.36	0.216	2.989	3.205
2025	64.08	-3.856	3.870	0.014
2030	36.62	-5.492	5.914	0.422
				$\hat{Y}$ = 8.753

TABLE E.11 Calculation of objective function in IS_1 and AS_1.

		LWR	FBR	PCT
IS_1	$\hat{X}$	35.915	7.141	55.460
	$\hat{Y}$	3.566	0.596	8.753
	C($)	24.181×10^9	4.527×10^9	51.338×10^9
AS_1	$\hat{X}$	46.083	0.0	52.420
	$\hat{Y}$	4.352	0.0	8.667
	C($)	30.208×10^9	0.0	49.607×10^9

Total cost:
IS_1: $80.046 billion *
AS_1: $79.815 billion

and B given in Table E.8. As an example, for LWR in AS_1, the calculation is

$$C = (0.3094\times10^9)(46.083) + (3.665\times10^9)(4.352)$$
$$= \$30.208\times10^9$$

Finally, the total costs of IS_1 and AS_1 are computed by adding the individual contribution from each technology in each case. The calculation for IS_1

*This figure does not account for increased cost of uranium after 2005 in IS_1. Thus the actual cost is even higher.

is

$$C_{total} = (24.181 + 4.527 + 51.338)(\$10^9) = \$80.046\times10^9$$

In Table E.11 we see that AS_1 has a lower value for the objective function, hence it would be favored by the model. Furthermore, it should be close to optimal under the assumption of increased cheap uranium. The value of the objective function for the optimal solution may well have a lower value than shown above for AS_1. The reason for this is that there is probably more installed capacity in AS_1 than is actually required. By keeping the total installed capacity in AS_1 equal to or greater than that in IS_1, it is guaranteed that the capacity constraints are satisfied. However, some of the underutilization in IS_1 may be due to obsolescence of LWR capacity after FBR is introduced. In AS_1, on the other hand, there would be no underutilization due to obsolescence of LWR, hence it may be possible to satisfy the capacity constraints in AS_1 with less installed capacity.

TABLE E.12. Installed LWR capacity in alternative scenario AS_2 — region V low.

	(1) Base load demand (GWyr/yr)	(2) Residual base load demand (GWyr/yr)	(3) Minimum LWR capacity required (GW)	(4) Constraint on installed LWR capacity (GW)	(5) Annual buildup of LWR capacity (GW/yr)	(6) Constraint on annual buildup of LWR capacity (GW/yr)	(7) Annual retired LWR capacity (GW/yr)	(8) LWR capacity installed (GW)
1975	–	--	–	--	(0.085)			
1980	26.64	10.63	(15.12)	3.0	0.080	0.502	0.0	0.84
1985	36.45	16.99	(24.17)	8.0	0.496	0.496	0.0	3.32
1990	48.37	24.08	(34.25)	16.0	0.995	0.995	0.0	8.30
1995	62.39	30.22	(42.99)	28.0	1.594	1.594	0.0	16.27
2000	79.21	34.67	(49.32)	40.0	2.313	2.313	0.003	27.82
2005	97.44	36.61	(52.08)	56.0	3.176	3.176	0.085	43.27
2010	119.17	39.57	56.29	71.0	2.684	4.211	0.080	56.29
2015	143.71	44.56	63.39	91.0	2.305	3.621	0.496	65.34
2020	171.04	51.85	73.76	117.0	3.166	3.166	0.995	76.19
2025	200.49	61.05	86.84	150.0	4.199	4.199	1.594	89.22
2030	231.33	73.71	104.85	192.0	5.439	5.439	2.313	104.85
					$\hat{Y} = 3.957$			

TABLE E.13 Installed PCT capacity in alternative scenario (AS_2) — region V low.

	(1) Installed Capacity from IS_2 (GW)	(2) Minimum PCT Capacity Required (GW)	(3) Annual Buildup of PCT Capacity (GW/yr)	(4) Constraint on annual buildup of PCT Capacity (GW/yr)	(5) Annual Retired PCT Capacity (GW/yr)	(6) PCT Capacity Installed (GW)
1975	(32.00)					
1980	44.77	43.93	2.554	4.410	0.168	43.93
1985	63.76	60.44	3.599	3.976	0.297	60.44
1990	91.45	83.15	5.065	5.439	0.523	83.15
1995	120.57	104.30	5.268	7.491	0.922	104.88
2000	163.45	135.63	7.775	7.775	1.625	135.63
2005	157.73	114.46	0.5884	11.285	2.864	124.25
2010	161.57	105.28	1.224	1.224	2.554	117.60
2015	168.23	102.89	2.113	2.113	3.599	110.17
2020	177.83	101.64	3.359	3.359	5.065	101.64
2025	186.18	96.96	4.332	5.102	5.268	96.96
2030	187.69	82.84	4.951	6.465	7.775	82.84
			$\hat{Y}$ = 13.557			

E.4. Sensitivity with Respect to Cheap Uranium — Region V

In the text, it was stated that in the low scenario for region V, the entire contribution from FBR could be supplied at a lower cost with additional LWR capacity. This is shown in the calculations presented in Tables E.12 through E.17 below. Although this result suggests that the published IIASA scenario is not the optimal solution obtained from the model, it happens that the input data for this region differ in some respects from the technology data documented in DOGR, as shown in Figure E.10. As discussed below, these differences cause the model to produce the observed scenario.

In direct analogy with the previous example, IS_2 refers to the total contribution to electricity generation and installed capacity from LWR, FBR, and PCT in the original scenario. Similarly, AS_2 refers to the same contribution supplied with LWR and PCT only. The calculation is presented in Tables E.12 through E.17, and is identical to the calculation for region IV in all respects

TABLE E.14 Electricity generation and uranium extraction in AS_2 — region V low.

	(1) Total electricity generation (GWyr/yr)	(2) LWR electricity generation (GWyr/yr)	(3) PCT electricity generation (GWyr/yr)	(4) Annual uranium extraction (kt/y)	(5) Cumulative uranium extraction (kt)
1975	--				
1980	20.87	0.59	20.28	0.15	0.73
1985	30.87	2.33	28.54	0.67	4.07
1990	43.10	5.84	37.26	1.55	11.81
1995	55.23	11.44	43.79	2.86	26.09
2000	68.45	19.56	48.89	4.68	49.47
2005	73.69	30.42	43.27	7.02	84.58
2010	81.40	39.57	41.83	8.42	126.70
2015	86.20	45.34	40.86	9.07	172.03
2020	93.18	52.82	40.36	10.59	224.99
2025	100.48	62.00	38.48	12.46	287.31
2030	106.56	73.71	32.85	14.83	361.46
		$\hat{X}$ = 43.207	$\hat{X}$= 109.881		less than 363 kt (constraint on cheap uranium)

(hence it will not be described here in detail). The formats of Tables E.12, E.13, E.14, E.15, E.16, and E.17 are identical to those of Tables E.4, E.5, E.7, E.9, E.10, and E.11 respectively. The age structures for LWR and FBR are identical to those in region IV. The PCT age structure is again calculated from Equation (E.1), using the initial conditions r = 1.12 and 1975 installed capacity = 32.00 GW (DOGR, p.65).

In AS_2, LWR is used to fill the residual base load demand from 2010 onwards. In the year 2005, there is not sufficient LWR capacity to fill the entire residual base load demand, meaning that a small contribution from FBR would normally be installed during this particular time period. (The gap in installed LWR capacity is 52.08–43.27 = 8.81 GW in 2005; see Table E.12.) However, during this period there is sufficient excess installed PCT capacity to fill

TABLE E.15 Annual buildup of nuclear capacity in IS_2 — region V low.

	(1) Installed LWR Capacity (GW)	(2) Net annual LWR Buildup (GW/yr)	(3) Retired LWR Capacity (GW/yr)	(4) Annual LWR Buildup (GW/yr)	(5) Installed FBR Capacity (GW)	(6) Annual FBR Buildup (GW/yr)
1975	(0.44)	(0.085)		(0.085)		
1980	0.44	0.00	0.0	0.00	0.0	0.0
1985	0.44	0.00	0.0	0.00	0.0	0.0
1990	0.44	0.00	0.0	0.00	0.0	0.0
1995	1.54	0.220	0.0	0.220	0.0	0.0
2000	4.85	0.662	0.003	0.665	0.0	0.0
2005	10.41	1.112	0.085	1.197	2.00	0.400
2010	19.59	1.836	0.00	1.836	6.40	0.880
2015	32.61	2.604	0.00	2.604	13.67	1.454
2020	50.23	3.524	0.00	3.524	24.40	2.146
2025	72.27	4.408	0.220	4.628	39.28	2.976
2030	98.71	5.288	0.665	5.953	59.13	3.970
				$\hat{Y} = 1.438$		$\hat{Y} = 0.596$

TABLE E.16 Annual buildup of PCT capacity in IS_2 — region V low.

	(1) Installed Capacity (GW)	(2) Net annual Buildup (GW/yr)	(3) Annual Retired Capacity (GW/yr)	(4) Annual buildup (GW/yr)
1975	(32.00)			
1980	44.33	2.466	0.168	2.634
1985	63.32	3.798	0.297	4.095
1990	91.01	5.538	0.523	6.061
1995	119.03	5.604	0.922	6.526
2000	158.60	7.914	1.625	9.539
2005	145.32	-2.656	2.864	0.208
2010	135.58	-1.948	2.634	0.686
2015	121.95	-2.726	4.095	1.369
2020	103.20	-3.750	6.061	2.311
2025	74.63	-5.714	6.526	0.812
2030	29.85	-8.956	9.539	0.583
				$\hat{Y} = 15.195$

the gap (124.25−114.46 = 9.79 GW, see Table E.13), and therefore there is no contribution from FBR in AS_2.

TABLE E.17 Calculation of objective function in IS_2 and AS_2.

(a) documented cost assumptions

		LWR	FBR	PCT
IS_2	$\hat{X}$	16.189	7.141	129.759
	$\hat{Y}$	1.438	0.596	15.195
	$C(\$)$	10.279×10^9	4.527×10^9	105.582×10^9
AS_2	$\hat{X}$	43.207	0.0	109.881
	$\hat{Y}$	3.957	0.0	13.557
	$C(\$)$	27.871×10^9	0.0	91.305×10^9

Total cost:

IS_2	\$120.388 billion
AS_2	\$119.176 billion

(b) actual cost assumptions

		PCTa	PCTb
IS_2	$\hat{X}$	95.233	34.525
	$\hat{Y}$	14.776	0.419
	$C(\$)$	66.752×10^9	18.126×10^9
AS_2	$\hat{X}$	82.925	26.957
	$\hat{Y}$	12.694	0.863
	$C(\$)$	57.815×10^9	15.627×10^9

Total cost:

IS_2	\$ 99.684 billion
AS_2	\$101.313 billion

The purpose of this example is to show that there exists a feasible solution AS_2 which completely excludes FBR, and yet has a lower total cost than the documented IIASA scenario (IS_2). It is possible that the optimal solution from the model would include a small contribution from FBR (assuming the standard input data for PCT). The reason for this is that there is not enough cheap uranium to fill the residual base demand with LWR alone throughout the time horizon. Thus the model would optimize the timing of the contribution from LWR. If LWR was introduced at the maximum possible buildup rate from 1980 onwards, there might be a small contribution from FBR towards the end of the time horizon, provided that the installed LWR capacity was not excessively underutilized as a consequence. On the other hand, if the contribution from LWR was chosen so as to fulfill the residual base demand later in the time horizon (as it is in AS_2), then there would be no contribution from FBR at all. In any case, the contribution from FBR would be at most very small.

Rerun Region 5 low
ELECTRICITY GENERATION
BY TECHNOLOGY

units: GWel

1980	0.31	0.	0.	20.56	0.	0.	16.01	0.	1.13
1985	0.31	0.	0.	30.56	0.	0.	19.46	0.	1.67
1990	0.31	0.	0.	42.79	0.	0.	24.29	0.	1.62
1995	1.08	0.	0.	54.15	0.	0.	32.17	0.	1.59
2000	3.40	0.	0.	65.05	0.	0.01	44.54	0.	0.
2005	7.29	0.	1.40	65.00	0.	0.38	60.83	0.	3.61
2010	13.72	0.	4.48	63.20	0.	2.64	79.60	0.	6.56
2015	22.84	0.	9.58	53.79	0.	10.70	99.15	0.	9.34
2020	35.04	0.	17.09	41.05	0.	20.52	119.19	0.	11.70
2025	43.28	0.	27.51	29.69	0.	33.50	139.44	0.	13.57
2030	53.28	0.	41.41	11.87	0.	51.68	157.62	0.	15.54
	$\hat{X}$=16.189		$\hat{X}$= 7.141	$\hat{X}$=129.759					

	+ lwr	x c-lwr	a fbr	> coal	v c-coal	< advcoa	+ hydro	x solar	a petg
1980	0.31	0.31	0.31	20.87	20.87	20.87	36.87	36.87	38.00
1985	0.31	0.31	0.31	30.87	30.87	30.87	50.33	50.33	52.00
1990	0.31	0.31	0.31	43.10	43.10	43.10	67.38	67.38	69.00
1995	1.08	1.08	1.08	55.23	55.23	55.23	87.41	87.41	89.00
2000	3.40	3.40	3.40	68.45	68.45	68.46	113.00	113.00	113.00
2005	7.29	7.29	8.69	73.69	73.69	74.57	135.39	135.39	139.00
2010	13.72	13.72	18.20	81.40	81.40	84.04	163.64	163.64	170.20
2015	22.84	22.84	32.41	86.20	86.20	96.91	196.06	196.06	205.40
2020	35.04	35.04	52.13	93.18	93.18	113.71	232.90	232.90	244.60
2025	43.28	43.28	70.79	100.48	100.48	133.99	273.43	273.43	287.00
2030	53.28	53.28	94.69	106.56	106.56	158.24	315.86	315.86	331.40

FIGURE E.7 Electricity generation results from the IIASA scenario — region V low.

As an aside, if the constraint on cheap uranium were increased from 363 kt to 396 kt, then FBR would definitely not appear in the optimal solution (again, assuming the standard input data for PCT). In this case, there would be sufficient cheap uranium to supply the entire residual base load demand with cheap LWR from 2005 onwards, and to meet the maximum supply constraint for LWR prior to 2005. The calculation for this case is shown in Table E.18, and it follows the exact same logic as the previous calculations.

The final IIASA scenario results for electricity generation, installed capacity, and uranium extraction are shown in Figures E.7, E.8, and E.9, respectively.

TABLE E.18 Alternative scenario with increased cheap uranium — region V low.

	(1) Minimum LWR capacity required (GW)	(2) Annual buildup of LWR capacity (GW/yr)	(3) Constraint on annual buildup of LWR capacity (GW/yr)	(4) Annual retired LWR capacity (GW/yr)	(5) LWR capacity installed (GW/yr)	(6) LWR electricity generation (GW)	(7) Annual uranium extraction (GWyr/yr)	(8) Cumulative uranium extraction (kt)
1980	3.0	0.51	0.51	0.0	3.0	2.1	0.63	3.2
1985	8.0	1.00	1.00	0.0	8.0	5.6	1.51	10.7
1990	16.0	1.60	1.60	0.0	16.0	11.2	2.82	24.8
1995	28.0	2.40	2.40	0.0	28.0	19.6	4.73	48.4
2000	44.0	3.20	3.20	0.003	44.0	30.8	7.14	84.1
2005	52.1	1.71	4.24	0.085	52.1	36.6	7.40	121.1
2010	56.3	1.933	2.45	0.51	59.2	40.7	8.04	161.3
2015	63.4	2.72	2.72	1.00	67.8	46.3	9.19	207.3
2020	73.8	3.66	3.66	1.60	78.1	53.6	10.68	260.7
2025	86.8	4.80	4.80	2.40	90.1	62.4	12.43	322.9
2030	104.9	6.16	6.16	3.20	104.9	73.7	14.75	396.6

Rerun Region 5 low
ELECTRICITY
INSTALLED CAPACITY

units: GWel

1930	0.44	0.	0.	44.33	0.	0.	18.20	0.	14.66
1965	0.44	0.	0.	63.32	0.	0.	22.13	0.	12.96
1990	0.44	0.	0.	91.01	0.	0.	27.62	0.	12.55
1995	1.54	0.	0.	119.03	0.	0.	36.59	0.	14.25
2000	4.85	0.	0.	158.60	0.	2.00	50.65	0.	18.96
2005	10.41	0.	2.00	145.32	0.	6.80	69.17	0.	27.99
2010	19.59	0.	6.40	135.58	0.	15.51	90.51	0.	50.94
2015	32.61	0.	13.67	121.95	0.	29.71	112.74	0.	72.51
2020	50.23	0.	24.40	103.20	0.	51.59	135.54	0.	90.78
2025	72.27	0.	39.28	74.63	0.	84.22	158.56	0.	105.31
2030	98.71	0.	59.13	29.85	0.	129.91	179.23	0.	120.59

	+ lwr	x c-lwr	a fbr	> coala	v c-coal	< advcoa	+ hydro	x solar	a petg
1930	0.44	0.44	0.44	44.77	44.77	44.77	62.97	62.97	77.64
1935	0.44	0.44	0.44	63.76	63.76	63.76	85.89	85.89	98.85
1990	0.44	0.44	0.44	91.45	91.45	91.45	119.06	119.06	131.62
1995	1.54	1.54	1.54	120.57	120.57	120.57	157.16	157.16	171.41
2000	4.85	4.85	4.85	163.45	163.45	165.44	216.10	216.10	235.06
2005	10.41	10.41	12.41	157.73	157.73	164.53	233.69	233.69	261.68
2010	19.59	19.59	25.99	161.57	161.57	177.08	267.59	267.59	318.53
2015	32.61	32.61	46.28	168.23	168.23	197.94	310.68	310.68	383.19
2020	50.23	50.23	74.63	177.83	177.83	229.43	364.96	364.96	455.75
2025	72.27	72.27	111.55	186.18	186.18	270.40	428.97	428.97	534.28
2030	98.71	98.71	157.84	187.69	187.69	317.60	496.83	496.83	617.42

FIGURE E.8 Electricity installed capacity results from the IIASA scenario — region V low.

Once again, there is less total coal burned for PCT in AS_2 than in IS_2. In this case, although the electricity generated from PCT in AS_2 exceeds that in

Rerun Region 5 low
NATURAL URANIUM
EXTRACTION

units: kt/yr

1980	0.05	0.
1985	0.05	0.
1990	0.05	0.
1995	0.27	0.
2000	0.85	0.
2005	1.74	0.
2010	3.10	0.
2015	4.97	0.
2020	7.43	0.
2025	9.29	0.
2030	11.54	0.

	curve 1 + uran 1	curve 2 x uran 2
1980	0.05	0.05
1985	0.05	0.05
1990	0.05	0.05
1995	0.27	0.27
2000	0.85	0.85
2005	1.74	1.74
2010	3.10	3.10
2015	4.97	4.97
2020	7.43	7.43
2025	9.29	9.29
2030	11.54	11.54

FIGURE E.9 Natural uranium extraction results from the IIASA scenario — region V low.

IS_2 during the final two time periods, there is plenty of excess coal extraction available to satisfy this increased consumption. Similarly, the total uranium consumption in AS_2 is 361.46 kt (see Table E.14), which is less than the input constraint on cheap uranium of 363 kt (DOGR, p.60). Thus, AS_2 is feasible within the existing resource and extraction constraints.

The contributions to the objective function from both IS_2 and AS_2 are computed as shown in Table E.17. The values shown in part (a) of the table are obtained using the standard cost assumptions documented in DOGR (which yield the cost coefficients shown in Table E.8). Since the total cost is lower for AS_2 than for IS_2, it is clear that the published IIASA scenario (IS_2) is not the optimal solution obtained from the model using the input cost data documented in DOGR. This raises questions as to how IS_2 was obtained.

(a)

NAME: coal, elec, a (Coal Fired Power Plant, Present Technology) REGION V

1975 capacity 32.00GW, growth parameter 12.0%/yr.

Buildup parameters: γ = 1.40, g = 0.40GW/yr.

Table 11. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	4.41	53.	37.
1985	6.57	85.	59.
1990	9.60	130.	91.
1995	13.84	195.	136.
2000	19.78	285.	200.
2005	0.	271.	190.
2010	0.	249.	174.
2015	0.	216.	151.
2020	0.	168.	118.
2025	0.	99.	69.
2030	0.	0.	0.

(b)

Coal Fired Power Plant, Present Technology

Name in the program: coal, elec, a
Length of plant life: 6 periods
Current costs: 23 $/kWyr
Capital costs: 550 $/kW
Maximal plant factor: 70 %
Fuel input (primary energy): 2.79 kWyr coal/kWyr

(c)

```
coal 1 a   1 6  1.      [9.  360.]     1.4 .4 ,  0.7   ; till plant fac
2.79 0. ,                                              ; foss fuel cons
0. , ,          , , ,   {PCTa}  , , ,                  ; nucl fuel cons
0. , , , , , , , ,                                     ; sec fuel cons
1.12 32.                                               ; till init cap
1 up 999. , , , ,        0. , , , , , , , ,            ; bnd1
1.12 32.                                               ; till init cap
1 up 999. , , , ,        0. , , , , , , , ,            ; bnd2
0                                                      ; dem sw
; end coal-electric

coal 1 b   1 6  1.      [23. 550.]     1.4 .4 ,  0.7   ; till plant fac
2.87 0. ,                                              ; foss fuel cons
0. , ,          , , ,   {PCTb}  , , ,                  ; nucl fuel cons
0. , , , , , , , ,                                     ; sec fuel cons
0. 0. 0         0. 0. 0          0                     ; till dem sw
;0. 0.  270.  2.  35.                                  ; env coeff
;0.9 0.59 2.
; end coal-electric (abated)
```

undocumented reduced costs for PCT

annual buildup eliminated from 2005 onwards

documented costs for PCT (DOGR, p. 94)

no bounds on annual buildup

FIGURE E.10 (a) Constraints on annual buildup of PCT in IIASA scenario — region V (reproduced from DOGR, p. 65). (b) Documented input data for PCT in IIASA scenarios (reproduced from DOGR, p.94). (c) Actual input data for PCT in IIASA scenario for region V (reproduced from computer input file).

The explanation lies in the fact that there are some differences between the input data given in DOGR and the corresponding figures that appear in the computer input file for IS_2. In Figures E.10(a) and (b) the documented input data for PCT in region V are reproduced from DOGR (pp. 65,94). Meanwhile, in Figure E.10(c), the corresponding data are reproduced from the computer input file for region V. From the latter we see that PCT is represented in the model by two distinct technologies, designated "coal 1a" and "coal 1b" (in Figure 10(c)). We shall refer to these as PCTa and PCTb, respectively. The second of these (PCTb) is the standard PCT technology that is documented in DOGR and is included in all of the IIASA scenarios.* Note that for PCTb the input data regarding current and capital costs (23. and 550., respectively) agree with the values given in DOGR (shown in part (b) of the figure). Furthermore, there are no restrictions or bounds on the buildup of PCTb, other than the usual buildup rate parameters. The other PCT technology in the input file (PCTa) incorporates two unusual features. Most importantly, the values of the input data for the current and capital costs (9. and 360., respectively) are considerably lower than those given in DOGR (23. and 550., see part (b) of the table). It is possible that PCTa is to be interpreted as PCT *without* a scrubber, whereas PCTb refers to (the documented) PCT with limestone scrubber (see Agnew *et al.*, 1979, p. 63). However, this is not discussed in either DOGR or EIFW, and in any case, the reduced cost data for PCTa are apparently not documented anywhere.

The other unusual feature of PCTa is that its annual buildup is set to zero from 2005 onwards. This is documented in DOGR, but it is somewhat confusing because DOGR specifies only one PCT technology, combining the buildup restriction for PCTa with the cost assumptions for PCTb.

*The fuel consumption for PCTb is 2.87 (kWyr coal/kWyr elec.), which is slightly higher than the usual Figure of 2.79 for PCT.

The major effect of the two PCT technologies is that during the first 25 years of the time horizon, PCT is available at significantly reduced cost. After the first five time periods, the cost of PCT jumps back up to its usual value. To compute the initial lower cost for PCT, we use Equation (E.3) with cap = 360 and cur = 9. This yields $ 121/kWyr in the base load region and $ 148/kWyr in the intermediate load region. Comparing these figures with those shown in Table E.3, it is clear that PCTa is the favored technology in both the base and intermediate load regions. Hence, under these cost assumptions, the optimal solution (IS_2) begins with a tremendous buildup of PCT initially (see column (4) of Table E.16). Meanwhile, there is zero buildup of LWR until 1995 (column (4) of Table E.15), at which time a small contribution from LWR is introduced in anticipation of the approaching cost jump for PCT (in 2005). Once LWR is introduced, it is built up at the maximum buildup rate throughout the remaining time horizon, but the resulting LWR contribution is considerably less than required to fill the residual base load demand (and furthermore, some of this limited LWR capacity is utilized in the intermediate load region after 2015). Hence FBR is introduced at its maximum buildup rate to supply base load power (since it is the next most competitive technology in the base load region; see Table E.3).

As indicated in Table E.17(b)*, under the new cost assumptions the IIASA scenario (IS_2) is indeed favored over the alternative scenario (AS_2). The overall conclusion is that, although FBR plays an important role in IS_2, it would

*One minor point should be mentioned regarding the calculation of the objective function in Table E.17(b). This was performed assuming that from 2010 onwards, all electricity generated from PCT in both AS_2 and IS_2 refers to PCTb. Actually this is not the case, because PCTa is still operated after 2005 (even though no further buildup of PCTa is permitted). However, the precise costs of AS_2 and IS_2 are not of particular importance here. The point is that the total cost of IS_2 is less than that of AS_2 under the new cost assumptions. If the electricity generated from PCTa and PCTb were carefully accounted for in computing the objective function, this would only widen the gap in cost between IS_2 and AS_2 (because there is more electricity generated from PCTa in IS_2 than in AS_2).

not have done so if the input cost data had been the figures documented in DOGR (see note on p.157).

E.5. Sensitivity with Respect to Cost Assumptions

In the text, it was stated that increasing the costs of nuclear power and the availability of coal in region I (low) produces a very different supply scenario (see Figure 15 of the text). In this example, IS_3 is the original IIASA electricity supply scenario for LWR, FBR, PCT, and ACT (advanced coal technology). Meanwhile, AS_3 supplies the same quantity of electricity with at least the same quantity of installed capacity, using mostly PCT and ACT, with a modest contribution from LWR. From Table E.3, it can be seen that if nuclear costs increase by 16%, then ACT and PCT are the favored technologies in both base and intermediate load regions.

REGION I

Table 4. Primary energy resources and man-made fuels, time series data.

	Max. Annual Coal Extraction (GWyr)		Max. Annual Oil Extraction (GWyr)		Max. Annual Oil Imports (GWyr)		Oil Import Costs ($/kWyr)		Annual Coal Exports (GWyr)	
	High	Low	High	Low	High	Low	High	Low	High	Low
1980	650	650	680	680	450	425	69	69	30	70
1985	900	800	685	780	435	295	87	87	105	60
1990	1100	900	935	880	220	190	106	96	140	40
1995	1250	950	1065	970	130	95	106	96	150	0
2000	1500	1000	1235	1065	0	0	106	96	150	0
2005	1700	1200	1305	1090	0	0	106	96	150	0
2010	1900	1400	1320	1110	0	0	106	96	170	0
2015	2000	1600	1225	1135	0	0	106	96	400	0
2020	2200	1800	1140	1020	0	0	106	96	500	0
2025	2400	2000	850	625	0	0	106	96	750	0
2030	2700	2000	850	625	0	0	106	96	750	0
		71.5 TWyr								

FIGURE E.11 Assumed primary fossil fuel constraints in the IIASA scenarios — region I (from DOGR, p.14).

The calculation begins with the computation of the excess coal available in the scenario. The assumed constraint on coal extraction is shown in Figure E.11 (circled column), and the total coal consumed in IS_3 is shown in Figure E.12 (circled column). The arithmetic difference of these two is the annual excess coal available, shown in column (1) of Table E.19. To determine the total quantity of excess coal available, the numbers in this column are added and the sum is multiplied by 5. This gives a total of 28.315 TWyr of excess coal available, as shown.

TABLE E.19 Displacement of nuclear power by coal-fired power in AS_3 — region I low.

	(1) Excess coal available (GWyr/yr)	(2) Maximum additional electricity generation ACT (GWyr/yr)	(3) Remaining excess coal (GWyr/yr)	(4) Maximum additional electricity generation PCT (GWyr/yr)	(5) Maximum Additional electricity generation (GWyr/yr)	(6) Total nuclear electricity generation in IS_3 (GWyr/yr)	(7) Minimum LWR contribution in AS_3 (GWyr/yr)
1980	0.0	0.0	0.0	0.0	0.0	41.9	41.9
1985	0.0	0.0	0.0	0.0	0.0	64.8	64.8
1990	84.9	0.0	85.0	30.5	30.5	99.1	68.6
1995	196.2	3.0	188.7	67.6	70.6	146.8	76.2
2000	314.6	16.2	274.1	98.2	114.4	207.3	92.9
2005	604.3	55.8	464.8	166.6	222.4	272.8	50.4
2010	923.2	169.0	500.7	179.5	348.5	357.7	9.2
2015	1095.8	365.9	181.1	64.9	430.8	394.2	0.0
2020	1087.4	435.0	0.0	0.0	435.0	420.7	0.0
2025	906.9	362.8	0.0	0.0	362.8	467.1	(104.3)
2030	449.7	179.9	0.0	0.0	179.9	491.2	(311.3)
	28.315 TWyr						

The fuel consumption of the two coal technologies PCT and ACT (per kWyr of electricity produced) is 2.79 kWyr and 2.50 kWyr, respectively. Since the latter is more fuel efficient, it will be utilized as much as possible in AS_3. The PCT contribution is bounded above by the supply constraint, shown in Figure E.13 (circled column). Subtracting from this the ACT electricity generation in IS_3 (upper "advcoal" column in Figure E.14), we obtain the maximum additional electricity that could be generated from ACT, shown in column (2) of Table E.19. From 2020 onwards, these numbers are limited by the quantity of excess coal available, rather than the supply constraint. Multiplying column (2) by the fuel consumption (2.5 kWyr coal/kWyr), and subtracting from column (1) we obtain the remaining excess coal (column (3)). Dividing this by

Perun
USES OF
COAL

units: GW

1980	112.00	468.00	0.	0.	70.00	0.	0.
1985	134.00	606.00	0.	0.	60.00	0.	0.
1990	154.00	621.14	0.	0.	40.00	0.	0.
1995	172.00	581.83	0.	0.	0.	0.	0.
2000	189.00	495.16	1.24	0.	0.	0.	0.
2005	206.00	388.45	1.24	0.	0.	0.	0.
2010	220.00	235.69	21.08	0.	0.	0.	0.
2015	231.00	169.85	103.34	0.	0.	0.	0.
2020	238.00	164.14	310.46	0.	0.	0.	0.
2025	241.00	132.02	720.04	0.	0.	0.	0.
2030	242.00	129.38	1178.96	0.	0.	0.	0.

	curve 1 + solid	curve 2 x elec	curve 3 a liquid	curve 4 > gaseou	curve 5 v export	curve 6 < comb	curve 7 + bheat
1980	112.00	580.00	580.00	580.00	650.00	650.00	650.00
1985	134.00	740.00	740.00	740.00	800.00	800.00	800.00
1990	154.00	775.14	775.14	775.14	815.14	815.14	815.14
1995	172.00	753.83	753.83	753.83	753.83	753.83	753.83
2000	189.00	634.16	685.40	685.40	685.40	685.40	685.40
2005	206.00	594.45	595.69	595.69	595.69	595.69	595.69
2010	220.00	455.69	476.77	476.77	476.77	476.77	476.77
2015	231.00	400.85	504.19	504.19	504.19	504.19	504.19
2020	238.00	402.14	712.60	712.60	712.60	712.60	712.60
2025	241.00	373.02	1093.07	1093.07	1093.07	1093.07	1093.07
2030	242.00	371.38	1550.34	1550.34	1550.34	1550.34	1550.34

FIGURE E.12 Uses of coal results from the IIASA scenarios — region I low.

the PCT fuel consumption (2.79 kWyr coal/kWyr), we obtain the maximum additional electricity that could be produced from PCT (column (4)). Adding this to column (2) we obtain the maximum quantity of electricity that could be produced with the excess coal (column (5)). Since this will displace nuclear power, we subtract it from the total nuclear contribution in IS_3 (column (6), which is copied from Figure E.14), to obtain the minimum required contribution from nuclear power in AS_3 (column (7)). In the last two time periods, the small quantity of excess coal available would imply a rather large contribution from nuclear power, as shown in parentheses in column (7). In AS_3, we replace these last two terms with zeroes; and then compute the additional quantity of coal required to fill the resulting gap. As will be seen below, this turns out to be an insignificant increase that is well within the assumed constraint on availability of cheap coal (category I).

We now begin the specification of AS_3. The nuclear contribution will be filled entirely by LWR, since it is less costly than FBR. Furthermore, this power

TABLE E.20 LWR in AS_3 — region I low.

	(1) Minimum LWR installed (GW)	(2) Annual buildup (GW/yr)	(3) Constraint on annual buildup (GW/yr)	(4) Retired capacity (GW/yr)	(5) Installed capacity (GW)	(6) Electricity generation (GWyr/yr)
1975	(39.00)					
1980	59.8	4.18	9.88	0.02	59.8	41.9
1985	92.5	6.60	8.27	0.06	92.5	64.8
1990	97.9	1.27	11.90	0.19	97.9	68.6
1995	108.8	2.89	3.91	0.56	109.5	76.7
2000	132.6	6.335	6.335	1.72	132.6	92.9
2005	72.0	0.0	11.50	5.25	106.4	74.5
2010	13.1	0.0	2.0	4.18	85.5	59.9
2015	0.0	0.0	2.0	6.60	52.5	36.8
2020	0.0	0.0	2.0	1.27	46.1	32.3
2025	0.0	0.0	2.0	2.89	31.7	22.2
2030	0.0	0.0	2.0	6.335	0.0	0.0
		$\hat{Y}$ = 13.002				$\hat{X}$ = 196.166

will be utilized in the base load, so the load factor will be 0.70. Dividing the figures in column (7) of Table E.19 by this load factor, we obtain the minimum required installed LWR capacity in AS_3, shown in column (1) of Table E.20. The remaining columns in this table are generated in exactly the same fashion as described above for AS_1 and AS_2. The age structure for LWR (column (4)) is calculated from Equation E.1 with the initial conditions c_0 = 39.00GW and r = 1.25 (DOGR, p. 15). The LWR electricity generation (column (6)) is calculated assuming full utilization of the installed capacity. This is because the operating cost for LWR is less than that for coal-fired power, so the dwindling LWR capacity is fully utilized in base load. The data in column (6) are plotted cumulatively in Figure 15(b) of the text.

The next step in specifying AS_3 is to describe the installed capacity of PCT and ACT. As in the previous examples, the total installed capacity in AS_3 is kept at least as high as in IS_3. The total installed nuclear and coal capacity for IS_3 is shown in Figure E.15 (circled column).

REGION I

NAME: advcoal, elec, a (Coal-Fired Power Plant, Advanced Technology)

1975 capacity 0.GW, growth parameter 0.%/yr.

Buildup parameters: Y = 2.00, g = 2.00GW/yr.

Table 9. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	0.	0.	0.
1985	0.	0.	0.
1990	0.	0.	0.
1995	2.00	10.	7.
2000	6.00	40.	28.
2005	14.00	110.	77.
2010	30.00	260.	182.
2015	62.00	570.	399.
2020	126.00	1200.	840.
2025	254.00	2460.	1722.
2030	510.00	4980.	3486.

FIGURE E.13 Assumed supply constraint for advanced coal technology (ACT) in the IIASA scenario — region I (from DOGR, p.17).

Rerun
ELECTRICITY GENERATION
BY TECHNOLOGY

units: GWel

	lwr	c-lwr	fbr	coal	c-coal	advcoa	hydro	solar	petg
1980	41.93	0.	0.	167.74	0.	0.	54.87	0.	50.46
1985	64.75	0.	0.	217.20	0.	0.	58.92	0.	20.13
1990	99.10	0.	0.	222.63	0.	0.	63.37	0.	19.90
1995	146.79	0.	0.	204.98	0.	3.98	68.34	0.	21.91
2000	207.31	0.	0.	166.89	0.	11.81	73.32	0.	21.67
2005	272.00	0.	0.79	120.26	0.	21.17	78.04	0.	18.74
2010	348.31	0.	9.36	72.82	0.	13.01	82.49	0.	12.01
2015	360.68	0.	33.50	31.23	0.	33.09	86.66	0.	16.84
2020	331.86	0.	88.78	9.06	0.	55.55	90.53	0.	12.21
2025	260.74	0.	206.35	0.	0.	52.81	94.09	0.	0.
2030	189.78	0.	301.38	0.	0.	51.75	97.09	0.	0.
	$\hat{X}=435.677$		$\hat{X}=38.899$	$\hat{X}=551.143$		$\hat{X}=24.976$			

	+ lwr	x c-lwr	a fbr	> coal	v c-coal	< advcoa	+ hydro	x solar	a petg
1980	41.93	41.93	41.93	209.67	209.67	209.67	264.54	264.54	315.00
1985	64.75	64.75	64.75	281.95	281.95	281.95	340.87	340.87	361.00
1990	99.10	99.10	99.10	321.73	321.73	321.73	385.10	385.10	405.00
1995	146.79	146.79	146.79	351.77	351.77	355.75	424.09	424.09	446.00
2000	207.31	207.31	207.31	374.20	374.20	386.01	459.33	459.33	481.00
2005	272.00	272.00	272.79	393.05	393.05	414.22	492.26	492.26	511.00
2010	348.31	348.31	357.67	430.48	430.48	443.49	525.99	525.99	538.00
2015	360.68	360.68	394.18	425.41	425.41	458.50	545.16	545.16	562.00
2020	331.86	331.86	420.65	429.71	429.71	485.25	575.79	575.79	588.00
2025	260.74	260.74	467.10	467.10	467.10	519.91	614.00	614.00	614.00
2030	189.78	189.78	491.16	491.16	491.16	542.91	640.00	640.00	640.00

FIGURE E.14 Electricity generation results from the IIASA scenario — region I low.

Rerun .
ELECTRICITY
INSTALLED CAPACITY

units: GWel

1980	59.87	0.	0.	282.27	0.	0.	109.84	0.	153.03
1985	92.45	0.	0.	341.36	0.	0.	117.95	0.	143.64
1990	141.50	0.	0.	358.79	0.	0.	126.86	0.	154.39
1995	209.60	0.	0.	334.98	0.	9.99	136.82	0.	170.02
2000	296.00	0.	0.	278.30	0.	39.98	146.78	0.	185.78
2005	388.38	0.	1.12	209.34	0.	86.60	156.23	0.	145.41
2010	497.33	0.	13.36	169.06	0.	100.96	165.15	0.	143.14
2015	515.00	0.	47.83	78.50	0.	139.68	173.50	0.	130.67
2020	432.79	0.	126.77	22.77	0.	227.10	181.25	0.	94.77
2025	411.87	0.	294.64	0.	0.	290.99	188.38	0.	49.94
2030	316.87	0.	430.32	0.	0.	295.03	194.38	0.	0.

	curve 1 + lwr	curve 2 x c-lwr	curve 3 a fbr	curve 4 > coala	curve 5 v c-coal	curve 6 < advcoa	curve 7 + hydro	curve 8 x solar	curve 9 a petg
1980	59.87	59.87	59.87	342.14	342.14	342.14	451.99	451.99	605.02
1985	92.45	92.45	92.45	433.81	433.81	433.81	551.76	551.76	695.40
1990	141.50	141.50	141.50	500.30	500.30	500.30	627.16	627.16	781.55
1995	209.60	209.60	209.60	544.58	544.58	554.57	691.39	691.39	861.41
2000	296.00	296.00	296.00	574.30	574.30	614.28	761.06	761.06	946.84
2005	388.38	388.33	389.50	598.84	598.84	685.44	841.67	841.67	987.08
2010	497.33	497.33	510.69	679.75	679.75	780.71	945.86	945.86	1089.00
2015	515.00	515.00	562.83	641.33	641.33	781.01	954.50	954.50	1085.17
2020	432.79	432.79	609.56	632.33	632.33	859.43	1040.68	1040.68	1135.45
2025	411.87	411.87	706.51	706.51	706.51	997.51	1185.88	1185.88	1235.82
2030	316.87	316.87	747.19	747.19	747.19	1042.22	1236.60	1236.60	1236.60

FIGURE E.15 Electricity installed capacity results from the IIASA scenarios — region I low.

Subtracting from this the installed LWR capacity in AS_3 (column (5) of Table E.20), we obtain the net coal capacity installed in AS_3, shown in column (1) of Table E.21. Since ACT is to be utilized as much as possible, the installed ACT capacity (column (2)) runs along the constraint (Figure E.13) up through 2010. Meanwhile, PCT is built up as needed, so that the sum of ACT and PCT installed capacity equals the required amount shown in column (1). After 2010, the buildup of PCT is discontinued, because ACT is able to meet all further buildup requirements. From 2015 onwards, the installed PCT capacity declines at the rate determined by its retired capacity (column (6)), and ACT capacity is installed as needed to fulfill the minimum required total coal capacity (column (1) of Table E.21). The resulting annual buildup of ACT is calculated in Table. E.22.

TABLE E.21 Installed PCT capacity in AS_3 — region I low.

	(1) Net coal capacity installed (GW)	(2) ACT installed (GW)	(3) PCT installed (GW)	(4) Annual PCT buildup (GW/yr)	(5) Constraint on annual PCT buildup (GW/yr)	(6) Retired PCT (GW/yr)
1975			(268.0)			
1980	282.3	0.0	282.3	8.04	29.60	5.18
1985	341.3	0.0	341.3	18.10	18.10	6.30
1990	402.4	0.0	402.4	19.88	38.20	7.66
1995	445.1	10.0	435.1	15.86	41.76	9.32
2000	481.7	40.0	441.7	12.66	33.72	11.34
2005	579.0	110.0	469.0	19.26	27.32	13.80
2010	695.2	260.0	435.2	1.28	40.52	8.04
2015	728.5	383.8	344.7	0.00	4.56	18.10
2020	813.3	568.0	245.3	0.00	2.00	19.88
2025	965.8	799.8	166.0	0.00	2.00	15.86
2030	1042.2	939.5	102.7	0.00	2.00	12.66
				$\hat{Y} = 47.109$		

TABLE E.22 Buildup of ACT in AS_3 — region I low.

	(1) Installed ACT capacity (GW)	(2) Annual buildup (GW/yr)	(3) Constraint on annual ACT buildup (GW/yr)	(4) Retired capacity (GW/yr)
1980	0.0	0.0	0.0	0.0
1985	0.0	0.0	0.0	0.0
1990	0.0	0.0	0.0	0.0
1995	10.0	2.00	2.0	0.0
2000	40.0	6.00	6.0	0.0
2005	110.0	14.00	14.0	0.0
2010	260.0	30.00	30.0	0.0
2015	383.8	24.76	62.0	0.0
2020	568.0	36.84	51.5	0.0
2025	799.8	48.36	75.7	2.00
2030	939.5	33.94	98.7	6.00
		$\hat{Y} = 15.727$		

The final step in specifying AS_3 is to allocate the total electricity generation (circled column in Figure E.14) to the various technologies. We begin by subtracting the LWR electricity generation (column (6) of Table E.20) from this total, to obtain the total electricity generated from coal-fired power in AS_3, shown in column (1) of Table E.23.* As mentioned above, we wish to utilize ACT to the full because it is more fuel efficient. However, the utilization of ACT capacity cannot just be set equal to the maximum plant capacity factor of 70%, because not all of this capacity is utilized in the base load region. Thus we must first determine what quantity of the total installed coal capacity is utilized in base load. In all scenarios for region I, hydropower is utilized only in the peak and intermediate load regions (DOGR, p.96), but not in base load. Thus the only other technology supplying base load power is LWR. Therefore, to calculate the residual base load shown in column (2) of Table E.23, we multiply the electricity demand (circled column in Figure E.16) by 70.1% (see Figure E.3) and subtract from this the LWR contribution (column (6) of Table E.20).

The amount of installed coal capacity utilized in base load (not shown in the table) is then determined by dividing the residual base demand by the maximum plant capacity factor (70%). This exceeds the installed ACT capacity up through 2015, so up until this time, the full ACT capacity is utilized in base load. During the last three time periods, however, the ACT installed capacity exceeds the requirements for base load, so some of it will be used in the intermediate and/or peak load regions. From Figures E.14 and E.16, it is clear that hydro and petg supply all peak demand plus some intermediate demand. This follows from the fact that the combined contribution of these two technologies exceeds 4.9% (peak load region; see Figure E.3) throughout the time horizon.

*These data are plotted (in a cumulative fashion) as the coal contribution in Figure 15(b) of the text.

REGION I

Table 2. Secondary energy demand (GWyr/yr).

	Electricity		Liquid Fuels		Solid Fuels		Gaseous Fuels		Soft Solar	
	High	Low	High	Low	High	Low	High	Low	High	Low
1980	327	315	956	936	116	112	688	666	9	8
1985	387	361	972	930	144	134	723	680	17	16
1990	448	405	1010	939	173	154	750	687	25	24
1995	509	446	1069	961	201	172	773	689	33	31
2000	569	481	1144	986	225	189	797	689	41	38
2005	625	511	1231	1010	242	206	826	690	49	45
2010	678	538	1323	1031	252	220	858	692	58	52
2015	730	562	1415	1054	260	231	890	694	65	58
2020	781	588	1502	1078	268	238	915	697	73	64
2025	831	614	1586	1104	276	241	935	699	79	69
2030	881	640	1668	1132	285	242	952	700	85	74

FIGURE E.16 Secondary energy demand projections in the IIASA scenarios — region I (from DOGR, p.12).

Thus both ACT and PCT are utilized in the base and intermediate load regions only. Therefore in order to utilize ACT capacity as much as possible during the final three time periods, the ACT electricity generation is calculated as follows. Taking 2025 as an example, the residual base demand is 408.2 GW/yr, which requires 408.2/0.7 = 583.1 GW capacity installed. ACT capacity is used for this purpose, and the remaining ACT capacity (799.8−583.1 = 216.7 GW) is used in the intermediate load region. Thus, the ACT electricity generation is given by

$$(583.1 \text{ GW})(0.7) + (216.7 \text{ GW})(0.398) = 494.4 \text{ GWyr/yr}$$

as shown in column (3) of Table E.23.

The electricity generated from PCT (column (5)) is obtained by subtracting the ACT generation (column (3)) from the total (column (1)).

Finally, to complete the specification of AS_3, we compute the total coal consumed for electricity generation. This simply amounts to multiplying columns (3) and (5) by the respective fuel consumption figures (2.5 for ACT,

TABLE E.23 Electricity generation in AS_3— region I low.

	(1) Total electricity generation from coal (GWyr/yr)	(2) Residual base demand (GWyr/yr)	(3) ACT electricity generation (GWyr/yr)	(4) Coal consumption ACT (GWyr/yr)	(5) PCT electricity generation (GWyr/yr)	(6) Coal consumption PCT (GWyr/yr)	(7) total coal consumption (GWyr/yr)	(8) Excess coal used (GWyr/yr)
1980	167.8	178.9	0.0	0.0	167.8	468.2	468.2	0.0
1985	217.2	188.3	0.0	0.0	217.2	606.0	606.0	0.0
1990	253.1	215.3	0.0	0.0	253.1	706.1	706.1	85.0
1995	279.1	235.9	7.0	17.5	272.1	759.2	776.7	194.9
2000	293.1	244.3	28.0	70.0	265.1	739.6	809.6	314.4
2005	339.7	283.7	77.0	192.5	262.7	732.9	925.4	536.9
2010	383.6	317.2	182.0	455.0	201.6	562.5	1017.5	781.8
2015	421.7	357.2	268.7	671.8	153.0	426.9	1098.6	928.8
2020	453.0	379.9	390.0	975.0	63.0	175.8	1150.8	986.7
2025	497.7	408.2	494.4	1236.0	3.3	9.2	1245.2	1113.2
2030	542.9	448.6	542.9	1357.3	0.0	0.0	1357.3	1227.9
			$\hat{X}$ = 172.497		$\hat{X}$ = 683.091			30.848 TWyr

2.79 for PCT), and adding them. The coal consumed by each technology is shown in columns (4) and (6), and the sum of these two is shown in column (7). To compute the excess coal consumed in AS_3, we subtract from column (7) the coal burned for electricity production in IS_3, which is given in Figure E.12 (upper row, second column). The result is shown in column (8). Comparing this with column (1) of Table E.19, we see that the excess coal available is exceeded in the final two time periods. Thus for AS_3 to be feasible, the last two coal extraction constraints in Figure E.11 must be increased by

1113.2–906.9 = 206.3 in 2025

1227.9–449.7 = 778.2 in 2030

The corresponding quantity of additional coal to be made available is (206.3 + 778.2) (5) = 4.922 TWyr. From Figure E.11, we see that an assumed 71.5 TWyr of coal are available for IS_3, so for AS_3 to be feasible, this figure must be increased to (71.5 + 4.92)TWyr = 76.42TWyr. Since there is a total of 174 TWyr of cheap coal available in region I (DOGR, p.13), this increase is well within the resource constraint. The required increase in coal available for extraction is

4.92/71.5 = 6.88%. However, this increase is almost twice as large as the actual increase in the quantity of coal required in AS_3. From column (8) of Table E.23 and column (1) of Table E.19, we see that the actual additional coal required in AS_3 is (30.848 − 28.315) TWyr = 2.533 TWyr, which is only 3.54% of the total 71.5 TWyr.*

By 2030, the contribution to electricity supply from coal-fired power in AS_3 is 542.9/640.0 = 84.8%, and the contribution from nuclear power is 0.0%. The corresponding shares in the original scenario (IS_3) are computed as follows. For coal-fired power, (0.0 + 51.8)/640.0 = 8.1%, and for nuclear power, (189.8 + 301.4)/640.0 = 76.7%.

TABLE E.24 Buildup of nuclear capacity in IS_3 — region I low.

	(1) Installed LWR capacity (GW)	(2) Net annual LWR buildup (GW/yr)	(3) Retired LWR capacity (GW/yr)	(4) Annual buildup of LWR (GW/yr)	(5) Installed FBR capacity (GW)	(6) Annual buildup of FBR (GW/yr)
1975	(39.00)					
1980	59.87	4.17	0.02	4.19	0.0	0.0
1985	92.45	6.52	0.06	6.58	0.0	0.0
1990	141.50	9.81	0.19	10.00	0.0	0.0
1995	209.60	13.62	0.56	14.18	0.0	0.0
2000	296.00	17.28	1.72	19.00	0.0	0.0
2005	388.38	18.48	5.25	23.73	1.12	0.22
2010	497.33	21.79	4.19	25.98	13.36	2.45
2015	515.00	3.53	6.58	10.11	47.83	6.89
2020	482.79	(-6.44)	10.00	3.56	126.77	15.79
2025	411.87	(-14.18)	14.18	0.00	294.64	33.57
2030	316.87	(-19.00)	19.00	0.00	430.32	27.14
				$\hat{Y}$ =35.675		$\hat{Y}$ = 3.330

Finally, we compare the value of the objective function in the two scenarios AS_3 and IS_3. For this purpose, the annual buildups for LWR, FBR, PCT, and ACT in IS_3 are calculated in the usual manner (Tables E.24 and E.25). The

*In any case, this is not a significant issue, because there is so much coal available in region I, and the additional coal is not required during the first 40 years of the time horizon.

TABLE E.25 Buildup of coal-fired capacity in IS_3 — region I low.

	(1) Installed PCT capacity (GW)	(2) Net annual PCT buildup (GW/yr)	(3) Retired PCT capacity (GW/yr)	(4) Annual PCT buildup (GW/yr)	(5) Installed ACT capacity (GW)	(6) Net annual ACT buildup (GW/yr)	(7) Retired ACT capacity (GW/yr)	(8) Annual ACT buildup (GW/yr)
1975	268.0				(0.0)			
1980	282.3	2.86	5.18	8.04	0.0	0.0	0.0	0.0
1985	341.4	11.82	6.30	18.12	0.0	0.0	0.0	0.0
1990	358.8	3.48	7.66	11.14	0.0	0.0	0.0	0.0
1995	335.0	-4.76	9.32	4.56	10.0	2.00	0.0	2.00
2000	278.3	-11.34	11.34	0.0	40.0	6.00	0.0	6.00
2005	209.3	-13.80	13.80	0.0	86.6	9.32	0.0	9.32
2010	169.1	-8.04	8.04	0.0	101.0	2.88	0.0	2.88
2015	78.5	-18.12	18.12	0.0	139.7	7.74	0.0	7.74
2020	22.8	-11.14	11.14	0.0	227.1	17.48	0.0	17.48
2025	0.0	-4.56	4.56	0.0	291.0	12.78	2.00	14.78
2030	0.0	0.00	0.00	0.0	295.0	0.80	6.00	6.80
				$\hat{Y} = 29.704$				$\hat{Y} = 7.134$

computed values for the weighted sums $\hat{X}$ and $\hat{Y}$ are summarized in Table E.26 for both IS_3 and AS_3. Calculating the objective function using the standard coefficients A and B (Table E.8), IS_3 is favored over AS_3, as expected. However, if the nuclear costs are increased by 16% or more, the situation is reversed, and AS_3 is favored. This demonstrates the serious lack of robustness in the supply scenarios with respect to variations in the cost assumptions.

To verify that AS_3 is favored under this cost increase, suppose the capital and current costs for LWR and FBR are increased as follows

	LWR	FBR
cur	\$50 → \$59.91	\$50 → \$58.00
cap	\$700 → \$817.28	\$920 → \$1067.20

From equations (E.8) and (E.9) the coefficients A and B have the new values:

	LWR	FBR
$A(\$10^9/\mathrm{GWyr})$	0.35895	0.29000
$B(\$10^9/\mathrm{GW})$	4.25140	5.33600

These coefficients are 16% greater than the values shown in Table E.8. The resulting costs of the nuclear contributions in IS_3 and AS_3 are $\$337.119\times10^9$ and $\$125.686\times10^9$ respectively, which lead to the total costs shown in Table E.26.

TABLE E.26 Calculation of objective function for AS_3 — region I low.

		LWR	FBR	PCT	ACT
IS_3	$\hat{X}$	435.68	38.90	551.14	24.98
	$\hat{Y}$	35.68	3.33	29.70	7.13
	C($)	265.58×10^9	25.04×10^9	352.66×10^9	30.05×10^9
AS_3	$\hat{X}$	196.17	0.0	683.09	172.50
	$\hat{Y}$	13.00	0.0	47.11	15.73
	C($)	108.35×10^9	0.0	465.40×10^9	127.01×10^9

Total cost:

IS_3: $673.33 billion
AS_3: $700.76 billion

Increase nuclear costs by 16%:

IS_3: $719.83 billion
AS_3: $718.10 billion

E.6. Electricity Supply System in Region VI

In region VI (Middle East and North Africa) there are 43 TWyr of gas available at $30/kWyr (DOGR, p. 72). There are no constraints imposed on the extraction rate for natural gas. The low cost of gas in this region affects the relative cost structure for electricity supply technologies. The cost ranking for the relevant technologies is shown in Table E.27. These figures are calculated using Equation (E.3) with rc = $30/kWyr for natural gas. LFP refers to liquid fuel power plants. The cost shown in Table E.27 for LFP is the operating cost for existing oil-fired capacity. No new LFP capacity is added, because the resulting product cost is so high ($256/kWyr in base load). Coal-fired power cannot contribute significantly in this region because there is essentially no coal (0.2 TWyr, DOGR, p.72).

TABLE E.27 Cost ranking of electricity supply technologies in region VI ($/kWyr).

Base	Intermediate	Peak
GFS 130	GT 147	GT 210
GT 134	GFS 155	GFS 276
LWR 136	LWR 192	PCT 401
FBR 143	PCT 196	LWR 465
PCT 154	FBR 214	FBR 556
		LFP (222)

From the table it is clear that the favored technologies are gas fired steam (GFS) for base load and gas turbines (GT) for intermediate and peak load. The gas consumption in region VI is shown in Figure E.17 for the high and low scenarios. In both cases, it is well below the 43 TWyr of cheap gas available. In Figure E.18 (a) and (b), the electricity generation results are shown for the high and low scenarios in region VI. The total nuclear contribution in these scenarios is 0.657 TWyr and 0.639 TWyr respectively. If these contributions were filled with the least efficient gas-fired technology (GT: 3.33 kWyr gas per kWyr electricity; DOGR, p.96), the additional gas consumption in the scenarios would be 2.188 TWyr and 2.128 TWyr respectively. This would increase the total gas consumption to 34.767 TWyr and 21.614 TWyr respectively, which are both well below the limit of 43 TWyr of cheap gas.

The installed capacity results for both scenarios in region VI are shown in Figure E.19. The assumed constraints for installed GFS and GT capacity are shown in Figure E.20 (reproduced from DOGR, pp.76,77). The sum of the installed capacities for GFS and GT is also shown in Figure E.20(b). By compar-

(a)

Rerun Region 6 high
GASEOUS FUEL SUPPLY
BY TECHNOLOGY

units: GW

1980	78.97	0.	0.	0.	0.	0.	0.
1985	122.41	0.	0.	0.	0.	0.	0.
1990	191.67	0.	0.	0.	0.	0.	0.
1995	287.28	0.	0.	0.	0.	0.	0.
2000	396.06	0.	0.	0.	0.	0.	0.
2005	519.35	0.	0.	0.	0.	0.	0.
2010	654.63	0.	0.	0.	0.	0.	0.
2015	811.71	0.	0.	0.	0.	0.	0.
2020	978.16	0.	0.	0.	0.	0.	0.
2025	1147.62	0.	0.	0.	0.	0.	0.
2030	1327.98	0.	0.	0.	0.	0.	0.

	curve 1	curve 2	curve 3	curve 4	curve 5	curve 6	curve 7
	+	x	a	>	v	<	+
	gas1	gas2	gas3	gas4	gasimp	advgas	export
1980	78.97	78.97	78.97	78.97	78.97	78.97	78.97
1985	122.41	122.41	122.41	122.41	122.41	122.41	122.41
1990	191.67	191.67	191.67	191.67	191.67	191.67	191.67
1995	287.28	287.28	287.28	287.28	287.28	287.28	287.28
2000	396.06	396.06	396.06	396.06	396.06	396.06	396.06
2005	519.35	519.35	519.35	519.35	519.35	519.35	519.35
2010	654.63	654.63	654.63	654.63	654.63	654.63	654.63
2015	811.71	811.71	811.71	811.71	811.71	811.71	811.71
2020	978.16	978.16	978.16	978.16	978.16	978.16	978.16
2025	1147.62	1147.62	1147.62	1147.62	1147.62	1147.62	1147.62
2030	1327.98	1327.98	1327.98	1327.98	1327.98	1327.98	1327.98

32.579 TWyr

(b)

Rerun Region 6 low
GASEOUS FUEL SUPPLY
BY TECHNOLOGY.

units: GW

1980	76.97	0.	0.	0.	0.	0.	0.
1985	115.69	0.	0.	0.	0.	0.	0.
1990	175.52	0.	0.	0.	0.	0.	0.
1995	245.17	0.	0.	0.	0.	0.	0.
2000	311.75	0.	0.	0.	0.	0.	0.
2005	372.11	0.	0.	0.	0.	0.	0.
2010	421.51	0.	0.	0.	0.	0.	0.
2015	470.41	0.	0.	0.	0.	0.	0.
2020	511.42	0.	0.	0.	0.	0.	0.
2025	567.99	0.	0.	0.	0.	0.	0.
2030	628.68	0.	0.	0.	0.	0.	0.

	curve 1	curve 2	curve 3	curve 4	curve 5	curve 6	curve 7
	+	x	a	>	v	<	+
	gas1	gas2	gas3	gas4	gasimp	advgas	export
1980	76.97	76.97	76.97	76.97	76.97	76.97	76.97
1985	115.69	115.69	115.69	115.69	115.69	115.69	115.69
1990	175.52	175.52	175.52	175.52	175.52	175.52	175.52
1995	245.17	245.17	245.17	245.17	245.17	245.17	245.17
2000	311.75	311.75	311.75	311.75	311.75	311.75	311.75
2005	372.11	372.11	372.11	372.11	372.11	372.11	372.11
2010	421.51	421.51	421.51	421.51	421.51	421.51	421.51
2015	470.41	470.41	470.41	470.41	470.41	470.41	470.41
2020	511.42	511.42	511.42	511.42	511.42	511.42	511.42
2025	567.99	567.99	567.99	567.99	567.99	567.99	567.99
2030	628.68	628.68	628.68	628.68	628.68	628.68	628.68

19.486 TWyr

FIGURE E.17 Gaseous fuel supply results from the IIASA scenario: (a) region VI high; (b) region VI low.

(a)

Rerun Region 6 high
ELECTRICITY GENERATION
BY TECHNOLOGY

units: GWel

1980	1.41	0.	0.	0.60	0.	0.	1.71	0.	10.28
1985	4.50	0.	0.	2.20	0.	0.	1.74	0.	16.56
1990	9.02	0.	0.	0.74	0.	0.	1.82	0.	28.42
1995	9.59	0.	0.	0.74	0.	0.	1.92	0.	46.96
2000	10.12	0.	0.	0.74	0.	0.	2.12	0.	68.23
2005	10.75	0.	0.	0.74	0.	0.	2.40	0.	92.51
2010	11.19	0.	1.41	0.49	0.	0.	2.76	0.	120.75
2015	8.80	0.	4.50	0.	0.	0.	3.11	0.	157.59
2020	4.98	0.	9.62	0.	0.	0.	3.48	0.	199.52
2025	5.12	0.	15.81	0.	0.	0.	3.83	0.	243.83
2030	5.29	0.	19.33	0.	0.	0.	4.29	0.	292.49

	lwr	c-lwr	fbr	coal	c-coal	advcoa	hydro	solar	petg
1980	1.41	1.41	1.41	2.01	2.01	2.01	3.72	3.72	14.00
1985	4.50	4.50	4.50	6.70	6.70	6.70	8.44	8.44	25.00
1990	9.02	9.02	9.02	9.76	9.76	9.76	11.58	11.58	40.00
1995	9.59	9.59	9.59	10.33	10.33	10.33	12.24	12.24	59.20
2000	10.12	10.12	10.12	10.85	10.85	10.85	12.97	12.97	81.20
2005	10.75	10.75	10.75	11.49	11.49	11.49	13.89	13.89	106.40
2010	11.19	11.19	12.60	13.09	13.09	13.09	15.85	15.85	136.60
2015	8.80	8.80	13.30	13.30	13.30	13.30	16.41	16.41	174.00
2020	4.98	4.98	14.60	14.60	14.60	14.60	18.08	18.08	217.60
2025	5.12	5.12	20.93	20.93	20.93	20.93	24.77	24.77	268.60
2030	5.29	5.29	24.63	24.63	24.63	24.63	28.91	28.91	321.40

0.657 TWyr

(b)

Rerun Region 6 low
ELECTRICITY GENERATION
BY TECHNOLOGY

units: GWel

1980	1.41	0.	0.	0.60	0.	0.	1.71	0.	10.28
1985	4.50	0.	0.	1.48	0.	0.	1.74	0.	16.29
1990	4.82	0.	0.	1.48	0.	0.	1.82	0.	27.89
1995	5.24	0.	0.	0.48	0.	0.	1.92	0.	41.57
2000	5.76	0.	0.	0.48	0.	0.	2.12	0.	53.84
2005	6.40	0.	0.	0.48	0.	0.	2.40	0.	65.92
2010	7.16	0.	1.41	0.23	0.	0.	2.76	0.	75.84
2015	8.07	0.	4.50	0.	0.	0.	3.11	0.	85.92
2020	11.67	0.	9.62	0.	0.	0.	3.48	0.	94.04
2025	11.95	0.	14.32	0.	0.	0.	3.83	0.	108.10
2030	12.12	0.	18.79	0.	0.	0.	4.29	0.	123.60

	lwr	c-lwr	fbr	coal	c-coal	advcoa	hydro	solar	petg
1980	1.41	1.41	1.41	2.01	2.01	2.01	3.72	3.72	14.00
1985	4.50	4.50	4.50	5.97	5.97	5.97	7.71	7.71	24.00
1990	4.82	4.82	4.82	6.29	6.29	6.29	8.11	8.11	36.00
1995	5.24	5.24	5.24	5.72	5.72	5.72	7.63	7.63	49.20
2000	5.76	5.76	5.76	6.24	6.24	6.24	8.36	8.36	62.20
2005	6.40	6.40	6.40	6.88	6.88	6.88	9.28	9.28	75.20
2010	7.16	7.16	8.56	8.80	8.80	8.80	11.56	11.56	87.40
2015	8.07	8.07	12.57	12.57	12.57	12.57	15.68	15.68	101.60
2020	11.67	11.67	21.28	21.28	21.28	21.28	24.76	24.76	118.80
2025	11.95	11.95	26.26	26.26	26.26	26.26	30.10	30.10	138.20
2030	12.12	12.12	30.92	30.92	30.92	30.92	35.20	35.20	158.80

0.639 TWyr

FIGURE E.18 Electricity generation supply results from the IIASA scenarios: (a) region VI high; (b) region VI low.

ing this with the total installed capacity in the scenarios (Figure E.19), it is clear that gas-fired power could be built up so as to equal or exceed the entire installed capacity in either scenario from 2005 onwards.

In sum, given the availability of cheap gas and the cost ranking in Table E.27, it appears that the optimal solutions for region VI would consist almost entirely of gas-fired power (mostly GFS in base load and mostly GT in intermediate and peak load). In particular, the optimal solutions would include little or no nuclear capacity. However, exogenous lower bounds were imposed on LWR buildup*, as shown in Figure E.21, so that LWR is forced to remain in the scenario. This explains the LWR contribution, but it is difficult to understand why FBR enters the solution, since it has a high relative cost in all load regions, and there appears to be an abundance of unused capacity among the cheaper technologies.

E.7. Projected Additions to Nuclear Capacity in the IIASA Scenarios

The assumed history of global LWR capacity installed is shown in Table E.28. The "Additions to capacity" are obtained in the same fashion as for region III (see Equation (E.1) and Table E.1). The totals in the last row of Table E.28 are entered into the "Retired capacity" column of Table E.29. The total installed nuclear capacity projections from the IIASA high and low scenarios are shown in Figure E.22 (circled columns). These data are copied into the first columns of Table E.29. The "New additions to capacity" are then calculated by adding the retired capacity to the net capacity added. For example, the calculation for the high scenario in 1995 is the following

Net capacity added = (587.94–388.53) GW = 199.41 GW

(199.41 + 5.58)GW = 204.99 GW

*These are mis-documented in DOGR as upper bounds.

(a)

Rerun Region 6 high
ELECTRICITY
INSTALLED CAPACITY

units: GWel

1980	2.01	0.	0.	1.89	0.	0.	3.43	0.	19.94
1985	6.42	0.	0.	5.72	0.	0.	3.48	0.	33.73
1990	12.88	0.	0.	5.72	0.	0.	3.64	0.	57.22
1995	13.69	0.	0.	5.72	0.	0.	3.84	0.	94.35
2000	14.44	0.	0.	5.72	0.	0.	4.25	0.	138.15
2005	15.35	0.	0.	5.72	0.	0.	4.81	0.	185.94
2010	15.98	0.	2.01	3.83	0.	0.	5.53	0.	246.09
2015	12.57	0.	6.42	0.	0.	0.	6.23	0.	323.41
2020	7.12	0.	13.73	0.	0.	0.	6.96	0.	408.56
2025	7.31	0.	22.58	0.	0.	0.	7.68	0.	501.63
2030	7.56	0.	27.60	0.	0.	0.	8.59	0.	601.73

	curve 1	curve 2	curve 3	curve 4	curve 5	curve 6	curve 7	curve 8	curve 9
	+	x	a	>	v	<	+	x	a
	lwr	c-lwr	fbr	coala	c-coal	advcoa	hydro	solar	petg
1980	2.01	2.01	2.01	3.90	3.90	3.90	7.33	7.33	27.26
1985	6.42	6.42	6.42	12.14	12.14	12.14	15.63	15.63	49.36
1990	12.88	12.88	12.88	18.60	18.60	18.60	22.24	22.24	79.46
1995	13.69	13.69	13.69	19.41	19.41	19.41	23.25	23.25	117.60
2000	14.44	14.44	14.44	20.16	20.16	20.16	24.41	24.41	162.56
2005	15.35	15.35	15.35	21.07	21.07	21.07	25.88	25.88	211.81
2010	15.98	15.98	17.99	21.82	21.82	21.82	27.34	27.34	273.43
2015	12.57	12.57	18.99	18.99	18.99	18.99	25.22	25.22	348.62
2020	7.12	7.12	20.85	20.85	20.85	20.85	27.81	27.81	436.37
2025	7.31	7.31	29.89	29.89	29.89	29.89	37.56	37.56	539.19
2030	7.56	7.56	35.16	35.16	35.16	35.16	43.75	43.75	645.48

(b)

Rerun Region 6 low
ELECTRICITY
INSTALLED CAPACITY

units: GWel

1980	2.01	0.	0.	1.89	0.	0.	3.43	0.	19.94
1985	6.42	0.	0.	3.71	0.	0.	3.48	0.	33.73
1990	6.88	0.	0.	3.71	0.	0.	3.64	0.	57.20
1995	7.48	0.	0.	3.71	0.	0.	3.84	0.	84.49
2000	8.23	0.	0.	3.71	0.	0.	4.25	0.	108.69
2005	9.13	0.	0.	3.71	0.	0.	4.81	0.	132.36
2010	10.22	0.	2.01	1.82	0.	0.	5.53	0.	154.88
2015	11.52	0.	6.42	0.	0.	0.	6.23	0.	178.74
2020	16.66	0.	13.73	0.	0.	0.	6.96	0.	200.04
2025	17.06	0.	20.44	0.	0.	0.	7.68	0.	231.22
2030	17.31	0.	26.83	0.	0.	0.	8.59	0.	265.15

	+	x	a	>	v	<	+	x	a
	lwr	c-lwr	fbr	coala	c-coal	advcoa	hydro	solar	petg
1980	2.01	2.01	2.01	3.90	3.90	3.90	7.33	7.33	27.26
1985	6.42	6.42	6.42	10.13	10.13	10.13	13.62	13.62	47.35
1990	6.88	6.88	6.88	10.59	10.59	10.59	14.23	14.23	71.42
1995	7.48	7.48	7.48	11.19	11.19	11.19	15.03	15.03	99.52
2000	8.23	8.23	8.23	11.94	11.94	11.94	16.19	16.19	124.87
2005	9.13	9.13	9.13	12.84	12.84	12.84	17.66	17.66	150.01
2010	10.22	10.22	12.23	14.04	14.04	14.04	19.57	19.57	174.45
2015	11.52	11.52	17.94	17.94	17.94	17.94	24.17	24.17	202.91
2020	16.66	16.66	30.39	30.39	30.39	30.39	37.35	37.35	237.39
2025	17.06	17.06	37.50	37.50	37.50	37.50	45.18	45.18	276.40
2030	17.31	17.31	44.14	44.14	44.14	44.14	52.73	52.73	317.87

FIGURE E.19 Electricity installed capacity results from the IIASA scenarios: (a) region VI high; (b) region VI low.

(a) REGION VI

NAME: gassteam, elec, a (Gas-Fired Steam Power Plant)

1975 capacity 10.00GW, growth parameter 5.0%/yr.

Buildup parameters: γ = 1.40, g = 0.40GW/yr.

Table 9. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	1.19	15.	11.
1985	2.06	24.	17.
1990	3.29	39.	28.
1995	5.01	63.	44.
2000	7.41	98.	69.
2005	10.77	149.	104.
2010	15.48	220.	155.
2015	22.07	320.	225.
2020	31.30	460.	323.
2025	44.22	656.	461.
2030	62.31	931.	654.

(b) REGION VI

NAME: jetgas, elec, a (Gas Turbines)

1975 capacity 0.GW, growth parameter 0.%/yr.

Buildup parameters: γ = 1.40, g = 0.40GW/yr.

Table 10. Implied theoretical upper limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Sum of constraints on installed gas-fired capacity	Maximum Output (GWyr/yr)
1980	0.40	2.	17	1.
1985	0.96	7.	31	5.
1990	1.74	16.	55	11.
1995	2.84	30.	93	21.
2000	4.38	52.	150	36.
2005	6.53	84.	233	59.
2010	9.54	130.	350	91.
2015	13.76	194.	514	136.
2020	19.66	284.	744	199.
2025	27.93	409.	1065	288.
2030	39.50	585.	1516	411.

FIGURE E.20 Assumed constraints for installed gas-fired capacity in the IIASA scenario — region VI (from DOGR, pp.76-77).

The retired capacity column is just the "New additions to capacity" column shifted vertically downwards by six time periods, as discussed in detail for previous examples.

REGION VI

NAME: u-lwr, elec, a (Light Water Reactor)

1975 capacity 0.GW, growth parameter 0.%/yr.

Buildup parameters: γ = 1.20, g = 0.40GW/yr.

Table 5. Implied theoretical ~~upper~~ lower limits.

	Annual Buildup (GW/yr)	Installed Capacity (GW)	Maximum Output (GWyr/yr)
1980	0.05	0.	0.
1985	0.07	1.	0.
1990	0.09	1.	1.
1995	0.12	2	1.
2000	0.15	2.	2.
2005	0.18	3.	2.
2010	0.20	4.	3.
2015	0.20	5.	3.
2020	0.20	5.	4.
2025	0.20	6.	4.
2030	0.20	6.	4.

FIGURE E.21 Lower bounds imposed on LWR installed capacity — region VI (from DOGR, p. 74). The phrase "Implied theoretical upper limits" in the table should read "Exogenous lower bounds".

To obtain the total capacity that is projected to be added over the next 50 years, the figures in the last columns of Table E.29 are added, producing the totals 5195.46 GW for the high scenario and 3213.19 GW for the low scenario. Since 1 GW = 1000 MW, these figures are equivalent to 5195 nuclear power stations of 1000 MW each in the high scenario (3213 power stations in the low scenario).

Since there are 18262 days in 50 years (365 × 50 + 12 for leap years), this means that on the average a new 1000 MW facility must be installed every 18262/5195 = 3.52 days in the high scenario, and every 18262/3213 = 5.68 days in the low scenario.

(a)

REGION - W HIGH DEMAND NEW REFERENCE
ELECTRICITY
INSTALLED CAPACITY

INPUT TABLE, UNITS: GW(EL)

1980	141.62	0.00	783.69	0.00	546,35	0.00	536.44	68,44
1985	241.22	0.00	908.15	0.00	590.09	0.00	610.46	90,73
1990	388.53	0.00	1238.35	0.00	637,66	0.00	764.50	116.98
1995	587.93	0.00	1466.06	39.82	694,89	0,00	823.56	133.53
2000	850.89	19,91	1637,44	163.28	762,48	0.00	798.04	158.51
2005	1199.88	95.41	1513.85	343.23	836,85	8.04	857.89	197,08
2010	1608.24	277,61	1421,13	508.05	915,13	24,20	959,83	230,07
2015	1937.45	667.51	1190.66	653.57	992,58	43,80	1008,96	332,73
2020	1967.87	1340.29	908.04	895.57	1067,74	51,82	1117.11	425.16
2025	1975.71	1965.41	663.16	1093.87	1139,25	56,46	1388,00	472,64
2030	1803.27	2573,98	497,49	1420.90	1208.00	75,74	1746,57	519,70

CUMULATIVE VALUES AS PLOTTED, UNITS: GW(EL)

	CURVE 1 LWR	CURVE 2 ADV,FB	CURVE 3 COAL	CURVE 4 ADVCOA	CURVE 5 HYDRO	CURVE 6 SOLAR	CURVE 7 PETG	CURVE 8 CPROD
1980	141.62	141.62	925.32	925.32	1471.67	1471,68	2008.12	2076.56
1985	241,22	241.22	1229.38	1229.38	1819.47	1819.47	2429.94	2520.67
1990	388.53	388.53	1626.88	1626.88	2264.55	2264,55	3029.05	3146.04
1995	587.93	587.94	2054.80	2094.63	2789.52	2789.52	3613.08	3746.61
2000	850.89	870.81	2508.25	2671.54	3434,03	3434,03	4232.07	4390.58
2005	1199.88	1295.29	2809.14	3152.38	3989.23	3997.27	4855.16	5052.24
2010	1608.24	1885.85	3306.98	3815.04	4730.17	4754.37	5714.21	5944.29
2015	1937.45	2604.96	3795.63	4449.20	5441.79	5485.59	6494.55	6827.29
2020	1967.87	3308.16	4216.21	5111.78	6179.52	6231.34	7348.45	7773.61
2025	1975.71	3941.12	4604.28	5698.15	6837.41	6893.87	8281.87	8754.51
2030	1803.27	4377.26	4874.76	6295.66	7503.66	7579.40	9325.97	9845.68

(b)

REGION - W LOW DEMAND NEW REFERENCE
ELECTRICITY
INSTALLED CAPACITY

INPUT TABLE, UNITS: GW(EL)

1980	129.63	0.00	771,94	0.00	546,35	0,00	519,01	66,73
1985	199.06	0.00	952,00	0.00	590,09	0.00	496,40	83,41
1990	300.97	0.00	1151,40	0.00	637,66	0,00	513.87	105,49
1995	441.59	0.00	1211,02	39.82	694,89	0.00	605,06	124,53
2000	621.05	10.55	1219.91	150.52	762,48	0,00	638,12	147,81
2005	815.77	60.34	1095.84	383.95	836,85	9,99	549.10	194,13
2010	1033.98	190.89	1000.20	474,77	915,13	16,68	594,10	195,54
2015	1093.55	477.39	767.30	598,03	992,58	16,68	669,06	223,12
2020	1093.70	849,05	494,06	769,64	1067.74	16,68	708,34	288,54
2025	1042.71	1327,63	310.25	945,08	1139,25	16,68	727,78	325,76
2030	907.54	1726.66	149,52	1144,70	1208,00	16,68	813,58	357,04

CUMULATIVE VALUES AS PLOTTED, UNITS: GW(EL)

	CURVE 1 LWR	CURVE 2 ADV,FB	CURVE 3 COAL	CURVE 4 ADVCOA	CURVE 5 HYDRO	CURVE 6 SOLAR	CURVE 7 PETG	CURVE 8 CPROD
1980	129.63	129.64	901.58	901.58	1447,94	1447,94	1966.95	2033.68
1985	199.06	199.07	1151.07	1151,07	1741.16	1741.16	2237.57	2320.98
1990	300.97	300.97	1452.37	1452.38	2090.04	2090.04	2603.91	2709.40
1995	441.59	441.59	1652.61	1692.43	2387.32	2387.32	2992,39	3116,92
2000	621.05	631.60	1851.51	2002,04	2764,52	2764,53	3402,65	3550,46
2005	815.77	876.12	1971.96	2355.91	3192,76	3202,76	3751.86	3945.99
2010	1033.98	1224.87	2225.07	2699.85	3614.98	3631.66	4225.76	4421,30
2015	1093.55	1570.94	2338.24	2936,27	3928,85	3945.53	4614,59	4837.71
2020	1093.70	1942.76	2436.82	3206.47	4274,21	4290.88	4999,22	5287.76
2025	1042.71	2370.34	2680.59	3625.68	4764,93	4781,61	5509,39	5835,15
2030	907.54	2634.20	2783.72	3928.43	5136.43	5153.11	5966.69	6323.73

FIGURE E.22 Electricity installed capacity results from the IIASA global scenarios: (a) high; (b) low scenario.

TABLE E.28 Assumed historical LWR age structure in IIASA scenarios.

Region	1975 Capacity	Additions to Capacity (GW) 1975	1970	1965	1960	1955	1950
I	39.00	26.25	8.61	2.82	0.93	0.31	0.10
II	10.00	6.73	2.21	0.73	0.24	0.08	0.02
III	28.00	18.85	6.18	2.03	0.67	0.22	0.07
IV	0.44	0.43	0.01	0.0	0.0	0.0	0.0
V	0.44	0.43	0.01	0.0	0.0	0.0	0.0
VI	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VII	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Totals:	77.88	52.69	17.02	5.58	1.84	0.61	0.19

The minimum and maximum values for the frequency of construction of nuclear generating stations in the scenarios are calculated as follows. First, there are 5(365) + 1 = 1826 days in 5 years.

	High scenario	Low scenario
1980:	1826/63.93 = 28.56 days/GW	1826/51.95 = 35.15 days/GW
2020:	1826/852.35 = 2.14 days/GW	
2025:		1826/573.78 = 3.18 days/GW

Note: The dual PCT technologies also appear in the computer input files for regions IV and VI, but they have little effect. This is because the dominant constraints are the scarcity of cheap uranium (region IV) and coal (region VI), as well as the small initial buildup rate Y_o.

TABLE E.29 IIASA's projection of global nuclear installed capacity (GW).

High Scenario

	Installed Capacity	Net Capacity Added	Retired Capacity	New Additions to Capacity
1975	(77.88)			
1980	141.62	63.74	0.19	63.93
1985	241.22	99.60	0.61	100.21
1990	388.53	147.31	1.84	149.15
1995	587.94	199.41	5.58	204.99
2000	870.81	282.87	17.02	299.89
2005	1295.29	424.48	52.69	477.17
2010	1885.85	590.56	63.93	654.49
2015	2604.96	719.11	100.21	819.23
2020	3308.16	703.20	149.15	852.35
2025	3941.12	633.96	204.99	837.95
2030	4377.26	436.14	299.87	736.01
				5195.46GW

Low Scenario

	Installed Capacity	Net Capacity Added	Retired Capacity	New Additions to Capacity
1975	(77.88)			
1980	129.64	51.76	0.19	51.95
1985	199.07	69.43	0.61	70.04
1990	300.97	101.90	1.84	103.74
1995	441.59	140.62	5.58	146.20
2000	631.60	190.01	17.02	207.03
2005	876.12	244.52	52.69	297.21
2010	1224.87	348.75	51.95	400.70
2015	1570.94	346.07	70.04	416.11
2020	1942.76	371.82	103.74	475.56
2025	2370.34	427.58	146.20	573.78
2030	2634.20	236.86	207.01	470.87
				3213.19GW

APPENDIX F: EARLY SENSITIVITY STUDIES

This Appendix provides a very brief summary of the early work on sensitivity analysis of the Häfele-Manne model, which is the forerunner of MESSAGE.

The Häfele-Manne (H-M) model is a linear programming model in which the sum of discounted costs of meeting a given demand for electrical and non-electrical energy is minimized, subject to various constraints. This basic structure was retained in all subsequent versions of the model (including MESSAGE). The inputs to H-M include cost assumptions for various technologies and constraints on the availability of fossil fuels and cheap uranium. For a full description, see Häfele and Manne (1974).

The first paper to be discussed here was published in October 1974 (Konno and Srinivasan, 1974). This paper explored the sensitivity of the H-M model to the assumed discount rate, costs and quantities of cheap uranium, cost of oil and gas, and a number of other parameters that are not particularly relevant to the present work. Some of the basic findings were the following: the model results are sensitive with respect to changes in the discount rate. In addition, the "supply pattern of energy changes widely as we vary the [petroleum] price," although the "total sum of energy consumed is less sensitive" (p. 10).

An interesting finding is that the model results are insensitive to the availability of cheap uranium, even though there is an LWR-step in this model as well. The reason for this is simple. The assumed static cost ranking for electricity generation in the H-M model is as shown in Table F.1 (from Suzuki and Schrattenholzer, 1974).

TABLE F.1

Technology	Annual cost ($\$10^9$/TW(thermal))
FBR	$31
LWR	$32 or $36
Coal	$46

It is clear from the table that the LWR-step has little effect, because it does not effect the relative cost ranking. The assumed cost per TW(th) of electricity generated from LWR varies between $32 billion and $36 billion, depending on the availability of cheap uranium. But this cost is always greater than the cost of FBR ($31 billion) and is always less than the cost of coal-fired electricity ($46 billion). Therefore, under these cost assumptions, the model results are not sensitive to the quantity of cheap uranium available.

The paper also explores the response of the model to the assumption that there exists a stock of uranium that is priced between the cheap and expensive categories. This simply replaces the single $4 billion LWR-step by two smaller LWR-steps which still add to $4 billion. The relative cost structure is therefore not affected in this case either, and so sensitivity is not observed.

The sensitivity of the H-M model results with respect to changes in the relative cost structure was not explored. For example, if the cost of FBR were increased by just 4% from ($31 billion to $32.24 billion), then the relative cost ranking would be altered, which could cause the model to produce very different results. In particular, sensitivity with respect to cheap uranium would probably be observed.

The next paper on sensitivity analysis was published in December 1974 (Suzuki and Schrattenholzer, 1974). This work investigates the sensitivity with respect to a parameter in H-M called the hydrogen utilization factor, which does not have a counterpart in MESSAGE. Nevertheless, it was found in some cases that variations in this parameter altered the relative cost structure, causing the model to produce optimal solutions that were significantly different from the solutions published in Häfele and Manne (1974).

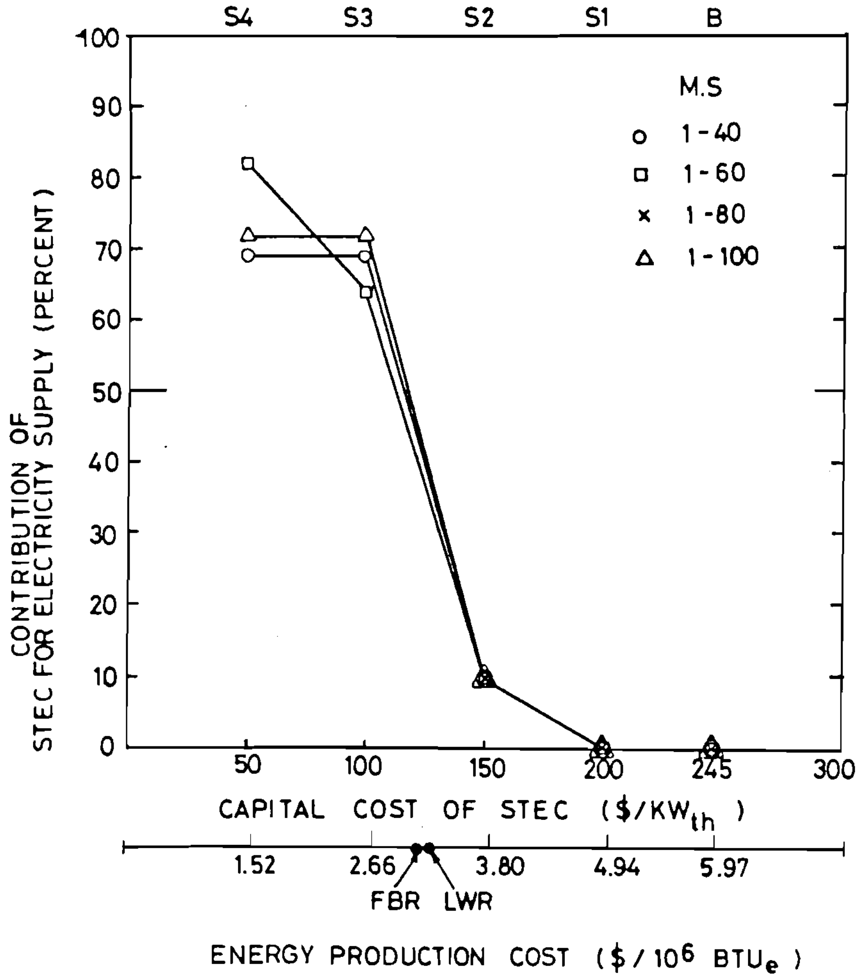


Figure 18. Contribution of solar thermal electric conversion system (STEC) for electricity supply versus capital cost of STEC.

FIGURE F.1 Early sensitivity analysis results on the contribution of solar thermal electric conversion (STEC) in the Häfele–Manne model (reproduced from Suzuki 1975, p.53).

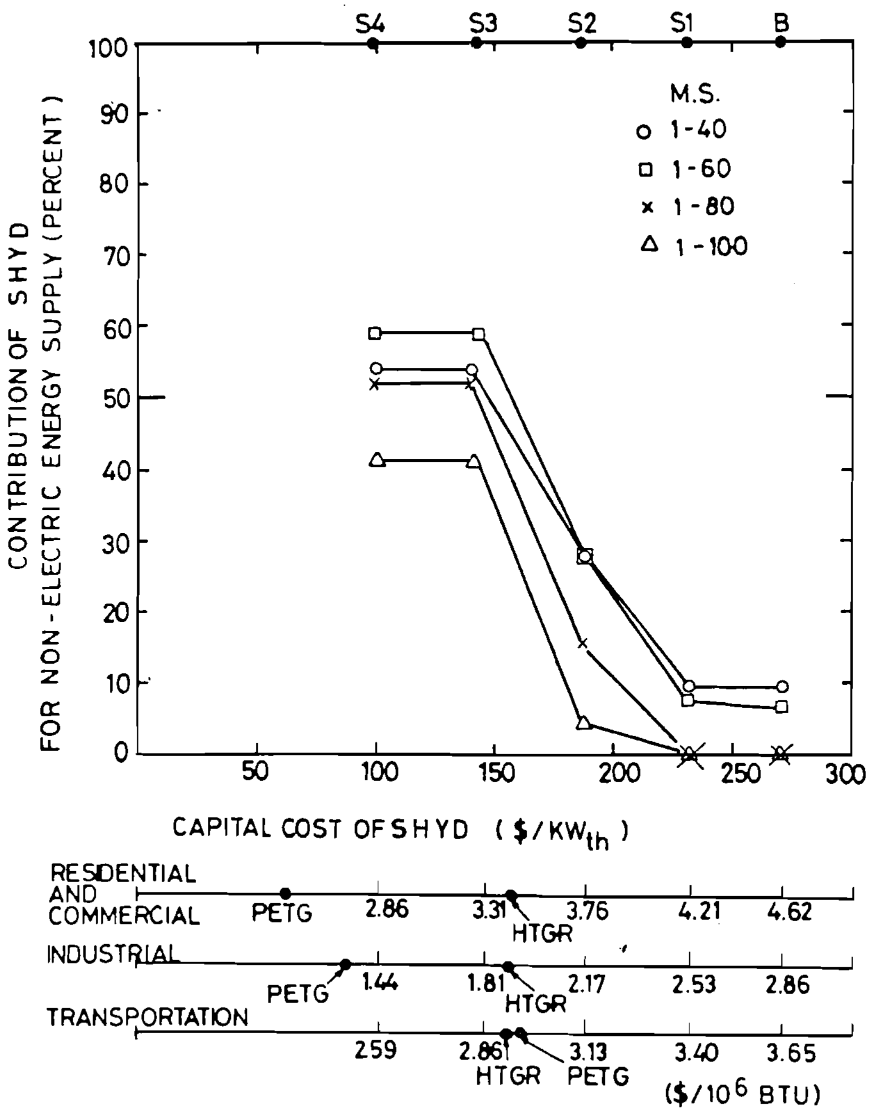


Figure 17. Contribution of solar hydrogen (SHYD) for non-electric energy supply versus capital cost of SHYD.

FIGURE F.2 Early sensitivity analysis results on the contribution of solar hydrogen (SHYD) in the Häfele–Manne model (reproduced from Suzuki 1975, p.51).

The final paper that includes documented sensitivity analysis was published in December 1975 (Suzuki, 1975). This paper investigates an extended version of the H-M model that includes solar thermal electric conversion (STEC) as an additional energy supply technology. Since the basic cost assumptions resulted in relatively high costs for electricity generated from

STEC, the contribution from this technology was insignificant in the base case scenarios. However, sensitivity analyses were conducted in which the assumed capital cost of STEC was varied, and this produced scenarios in which STEC contributed from 0% up to more than 70% of the total electricity supply. These results are shown in Figure F.1, which is reproduced from the report (p.53). Similar sensitivity was found in the non-electric energy supply system, as shown in Figure F.2 (also reproduced from the report, p.51).

Further sensitivity tests were conducted in which the cost of coal was varied. The result was that the contribution of coal-fired power to electricity supply varied from 10% to over 50%, as shown in Figure F.3 (reproduced from the report, p.59).

Note that the model has no knowledge of the physical interpretation of STEC. As far as the model is concerned, "STEC" is simply a set of numerical parameters that could represent any particular technology. Similarly, coal can represent any particular resource. Thus, the observed sensitivity to variations in the capital and resource costs is intrinsic to all energy supply technologies in the model.

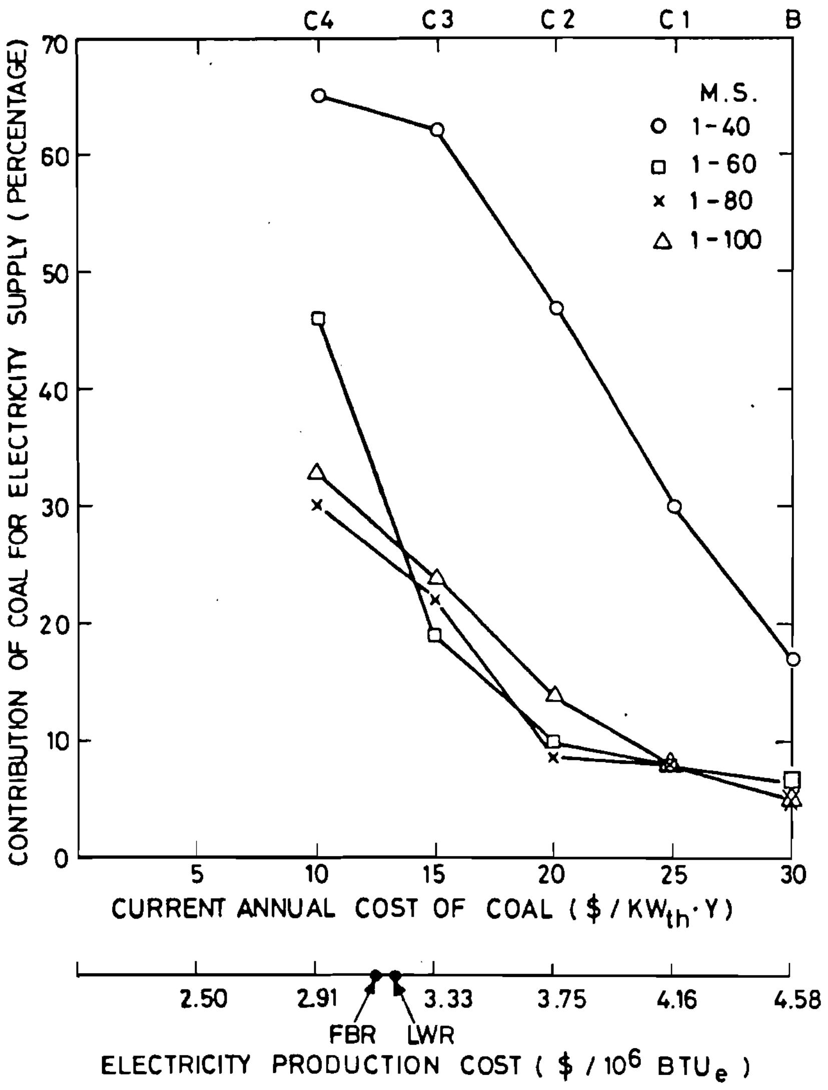


Figure 21. Contribution of coal to electricity supply versus current annual cost of coal.

FIGURE F.3 Early sensitivity analysis results on the contribution of coal in the Häfele–Manne model (reproduced from Suzuki 1975, p.59).

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