# THE ENERGY SUPPLY MODEL MESSAGE

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# FOREWORD

Providing sufficient amounts of energy has become a problem for many countries, in spite of minor fluctuations and short-term improvements. Furthermore, the longer the time horizon in view, the more difficult it is to work out schemes to meet prospective energy demand.

The Energy Systems Program at the International Institute for Applied Systems Analysis has studied this problem for the globe by focusing on the transition from the present energy system, still based on cheap fossil fuels, to one that will be more sustainable. The approach was to develop a linked set of models and procedures, each describing a part of the energy system, and to use them to construct two scenarios, one for high energy use and the other for low energy use, to describe possible development of the global energy system between 1980 and 2030. These scenarios and the work supporting their development are described in the publications emerging from this program. A comprehensive account is given in *Energy in a Finite World*: Volume 2, *A Global Systems Analysis*, Energy Systems Program Group of IIASA (1981), Wolf Häfele, Program Leader, (Cambridge, Massachusetts: Ballinger); a 200-page summary subtitled Volume I, *Paths to a Sustainable Future* is presented in a companion volume; and a 60-page Executive Summary is available from IIASA.

One of the models in the set used to describe the global energy system is the energy supply and conversion model with the acronym MESSAGE. It is a dynamic linear programming model that minimizes the total discounted costs of supplying a given set of energy demands over a given time horizon.

The purpose of this report is to supplement the scenario descriptions in the books cited above with a more complete technical description of the MESSAGE model. Thus, this report discusses the assumptions, the simplifications adopted in formulating the model, and its use in the global study. Its possible usefulness for other applications is also discussed briefly.

Two other publications dealing with MESSAGE are under preparation by the same author to complement the description presented here. The runs for the global scenarios will be recorded in *Documentation of the World Regions MESSAGE Runs* and the computer image generated by the model will be described in *A User's Guide for the MESSAGE Computer Program.*

WOLF HÄFELE
*Leader*
Energy Systems Program

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## SUMMARY

*This paper describes the general form of an energy supply model, called MESSAGE (Model for Energy Supply Systems And their General Environmental impact). MESSAGE is a dynamic linear programming model minimizing total costs of energy supply over a given time horizon. It balances secondary energy demand, which is disaggregated into sectors and exogenous to the model, with primary energy supply, given as a set of resource availabilities which are disaggregated into an optional number of cost categories by choosing from a given set of energy conversion technologies. Model constraints reflect the limited speed of build-up of technologies, the limited annual availability of resources, and technological relationships – among other aspects of the energy system. The model permits the definition of load regions (e.g., for electricity demand), distinguishes between indigenous and imported resources, takes account of the environmental impact of energy supply strategies, and optionally includes this impact in the objective function.*

*The most important application of MESSAGE so far has been in the description of the IIASA global energy scenarios. A set of models and formalized procedures, each describing one part of the energy system, is arranged in a loop. Iterative application of this model loop leads to globally consistent scenarios in the development of the global energy system. The most important connection for MESSAGE in this loop is with the energy demand model MEDEE-2 that provides the demand data for MESSAGE. Information on energy costs flows back to the demand model.*

*With this application in mind it was felt that the model description could be made more specific if some generality of the model features was omitted in favor of a clearer exposition. Thus, some variables that can be chosen by the model user to suit a particular application are replaced here by the values they assumed in the global study. A case in point is the description of the energy chain; here it stops at the level of secondary energy as in the global scenarios, whereas the generic model formulation also permits consideration of final or useful energy.*

*These replacements make it easier to understand the description of the model relations. However, the description does not allow decisions on the relevance of individual model runs. Such a judgment can be arrived at only by using this description together*

*with a full documentation of the model including the input data for a particular run. The IIASA runs for the global scenarios are documented in a separate forthcoming paper (Schrattenholzer 1982a). Another related publication is a user's guide for the computer program that generates the computer image of the model (Schrattenholzer 1982b).*

*Experience with the model has been useful in several respects. It appears that MESSAGE can also be used as a stand-alone model if the information, which in the global study came from other models of the IIASA model set, is collected by different means. The model can also be applied to geographical regions other than the world regions of the global study. In general, such applications may necessitate modifications of the original model but the basic features remain the same.*

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## 1 INTRODUCTION

Future energy supply is a problem of truly global concern and the subject of national and international debates. These debates diverge enormously. One reason is that there are many different perceptions of the energy system and these perceptions often pertain only to isolated aspects of its future development. This was the setting when the Energy Systems Program (ENP) at the International Institute for Applied Systems Analysis (IIASA) undertook to formulate consistent scenarios of the development of the global energy system. The scope of this work has included:

- The construction of plausible and consistent paths of development of the global energy system.
- The conceptualization of the dependence of the various subsystems on each other, and of the system boundaries.
- The embedding of the energy system into the economy.
- The economic and environmental impact of energy supply strategies.

On this basis, two scenarios, High and Low, of the global energy system over the next 50 years were formulated using the following guidelines:

- Consistency, to be understood as the establishment of a global balance between supply (by primary energy sources) and demand (for useful energy) and a balance between global exports and imports of primary energy.
- Reasonableness, according to expert judgment of the scenario assumptions and of the scenarios themselves. Obviously each step in the definition and selection of an expert, in their judgment on a first round of scenario results, and in the incorporation of this opinion is subjective. However, what remains at least establishes a reference point with which everybody can compare his own assumptions and perspectives.
- Continuity, so that the scenarios evolve smoothly from historical development and are themselves smooth. This does not mean, however, that the scenarios are extrapolations of past trends.
- Degree of variation. The difference between the High and the Low scenarios was to be large enough to cover an area within which the actual development is expected to fall with reasonably high probability.

These general considerations resulted in a global energy model or, better, in a set of submodels which together describe the global energy system. MESSAGE, a linear programming energy supply model, is one part of this model set.

The main purpose of this report is to document an important part of IIASA's global energy model enabling those who are interested to understand the tool with which the corresponding parts of the global scenarios were built up. Together with the documentation of the MESSAGE computer program and the model input data that were used for the description of the global scenarios (Schrattenholzer 1982a, b), this report should provide sufficient information for those with the appropriate experience to reproduce the MESSAGE results for the global scenarios in any desired degree of detail.

Thus, the report mainly addresses those already familiar with energy models. For the sake of conciseness much of the description of the real-world energy supply systems, that is the background of MESSAGE, has been omitted.

Section 2 gives a short summary of the model system used for the global scenarios; Section 3 describes the MESSAGE model; Section 4 briefly discusses general aspects of applications of MESSAGE and reports on experiences with its usage for countries and regions other than those used in the global study. Appendices give a summary of some high-level input data used for the global model runs, the description of a standard form of a dynamic linear programming model, and a classification of the model variables.

## 2 A GLOBAL ENERGY MODEL SET

To give an idea of the model environment in which MESSAGE was primarily used, this section describes briefly the model set used for the global energy scenarios. The actual application of this model set, the scenarios, and independent studies that have been integrated into the scenarios are given in the comprehensive report of the activities of IIASA's Energy Systems Program Group (1981).

A schematic description of the model set and the information flow between its submodels is given in Figure 1. The part above the dotted line, describing models and formalized procedures, was applied to each of seven world regions (defined in Appendix A), which together cover the globe. The parts of the large model for each world region are arranged in the form of a loop; the seven loops are connected by a procedure that balances interregional trade of primary energy.

Historically, the first step in formulating the scenarios was to make assumptions about the overall development of the economy (expressed as GDP per capita) and about population. However, after a first round of model runs, the built-in feedback mechanism changed the original assumptions so that there is no real "beginning" of the model loop. The output of this procedure as well as assumptions about the economic structure (GDP per sector), about lifestyle (e.g., dwelling space per capita), and about technical efficiencies (e.g., fuel efficiency of a car) are inputs to the energy consumption model MEDEE-2, which in turn produces scenarios of energy demand. (For a description of MEDEE-2 see Lapillone 1978.) These are converted into scenarios of secondary energy demand (by fuel type) using scenario assumptions for the allocation of demand for substitutable fuels to the various fuel types. The demands for secondary energy, maximum build-up rates, and cost figures are inputs into the MESSAGE model. MESSAGE results on the marginal

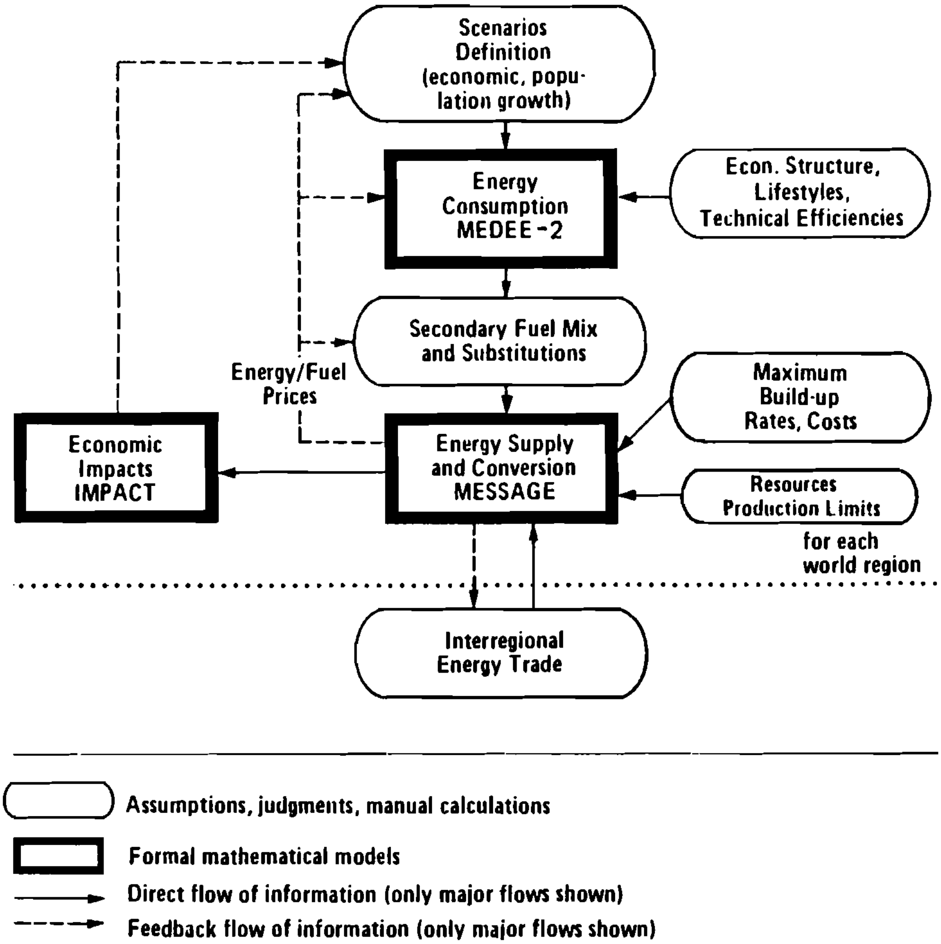


FIGURE 1 IIASA's global energy model.

costs of supplying secondary energy feed back into MEDEE-2. The other connection between MESSAGE and the model loop is with the procedure for the balance of global primary energy trade. Information about energy requirements flows from the world regional MESSAGE models into this procedure for energy trade, resulting in available imports for each region. The output of this procedure that is most important for the global scenarios is the development of the global oil market. Global availabilities of crude oil imports are based upon the assumption that the oil-exporting countries maximize the revenues from their exports and assumptions about the resource situation in the seven world regions. The results of MESSAGE are fed into the IMPACT model (Kononov and Pór 1979) which calculates the economic impact of energy supply strategies in terms of some economic variables (direct and indirect investments, land requirements, requirements for skilled labor, etc.) which are compared with the original assumptions on general economic development, thus closing the main model loop.

This loop is applied iteratively until satisfactory consistency is achieved.

## 3 GENERAL DESCRIPTION OF MESSAGE

The energy supply model MESSAGE (Model for Energy Supply Systems And their General Environmental impact) is a dynamic linear programming (DLP) model which minimizes total discounted costs of energy supply over a given time horizon. The main subject of the model is the balancing of demand for secondary (or final) energy and supply of primary energy resources via divers technologies. The most important model constraints reflect limits on the speed of build-up of technologies, the availabilities of indigenous and imported resources, and technological relationships. Major distinctive features of the model are the consideration of load regions for electricity demand, the disaggregation of resources into cost categories, and the consideration of the environmental impact of energy supply strategies. The model output is used to describe scenarios of energy supply. The description comprises the physical flows of energy between primary energy and eventual use as specified by the demand data, shadow prices of supply and demand constraints, and the environmental impact of energy supply paths, expressed as emissions and concentrations of pollutants. The energy flows give a consistent picture of the supply/demand balance; and the shadow prices allow for an assessment of the incremental benefit of additional resources, the incremental benefit of new technologies, and the marginal costs of meeting additional demand. The environmental module may be used to model the influence of emission or concentration standards (upper limits) on the model solution. Another possibility is the inclusion of emissions and/or concentrations of pollutants in the objective function.

Since this report gives only a general description of the model, it does not provide a solid basis for judging its results. Such a basis would have to include the whole set of input data which is documented elsewhere (Schrattenholzer 1982a). This documentation supplements the comprehensive report of the activities of IIASA's Energy Systems Program Group (1981). Another related publication is the user's guide for the computer program that generates the LP matrix in a standard format (Schrattenholzer 1982b). [The FORTRAN code generating a standard-format (MPS) LP matrix is available through the Energy Systems Program at IIASA.] In order to give at least some sense of the application of MESSAGE within the global scenarios, some higher level input data are summarized in Appendix A.

### 3.1 Model History

MESSAGE is the last in a series of LP energy models that were developed at IIASA. The first one was the Häfele–Manne model (Häfele and Manne 1974); this was followed by Suzuki's model (Suzuki 1975). The most significant differences distinguishing MESSAGE from its predecessors are the following: the inclusion of an optional number of primary energy resource categories allowing for the modeling of the nonlinear relation between extraction costs and available amount of a resource; the explicit consideration of demand load curves, in order to take account of e.g., the variation of demand for electricity; the calculation of residual discharges to the environment; increased program flexibility allowing e.g., for easy modular inclusion and removal of technologies. This flexibility has the disadvantage of somewhat blurring the distinctions between model, model inputs, and model input data. However, these distinctions will be discussed in some detail below.

The model history also includes stages in the development of MESSAGE as documented in Agnew et al. (1978, 1979). Agnew et al. (1979) describes an earlier concept of the model encompassing a part of the energy supply system significantly larger than considered for the actual global model runs. The restriction to the size described here was a consequence of the purpose of its application, the lack of sufficient data, and the level of detail to be incorporated. Agnew et al. (1978) is a user's guide for an earlier version of the computer program for the implementation of MESSAGE.

## 3.2 Model Relevance

In this section, questions of model credibility and model validity are discussed. These points precede the main model description as they establish the frame of reference for a part of the description. This section, containing some theoretical aspects, is an important part of the model description. However, it is not relevant to those using this report as an introduction to MESSAGE or as a reference, and may be omitted.

The validation of a model or, more generally, a discussion of model relevance would be a routine task if standard procedures were available and simply needed applying. Such procedures would have to be based on a general theory of systems and models. However, general and abstract concepts in mathematical system theory are not sufficiently familiar, nor widely accepted, among model builders and users nor are these concepts detailed enough to be used or referred to. Therefore two important aspects influenced the shape and content of this section. First, we emphasize the importance of model validation and second, as there are still no standard procedures of general systems and model theory to be followed, we take the freedom available to rearrange and modify existing theory in order to best combine general theory and particular model description. With this in mind, the following definitions should be considered merely as working definitions which are not exhaustive in the sense that they do not describe a complete theory. The reader who is further interested in theory is referred to Casti (1980) and Kalman (1974).

The first step is definition of a model as a description of a system. Accordingly, whenever a system is mentioned in connection with a model, the system being modeled is referred to. Where no confusion can arise, parts of the model are denoted by the same name as the relevant parts of the system.

The next step is a classification of models (Häfele 1980). This classification is not intended to be exhaustive, i.e., applicable to all models. Rather, it should distinguish between three important model types for which validation is quite different. The characteristic features of each type of model should therefore be viewed more as ingredients than as complete descriptions. This classification explains the background for the kind of model validation that was adopted for this report.

Three types of models are distinguished:

1. Models formulating laws of nature.
2. Models formulating regular behavior.
3. Models formulating concepts of controlling man-made systems.

The model attribute underlying this classification could – in accordance with Lewandowski (1980) – be called "model background." The description of the respective backgrounds for the three types of models would be natural, behavioral, and man-made. With respect to application, a more important model attribute is predictive capability. The above three types of models are ranked in decreasing order of predictive capability. The following discussions give a more detailed characterization of the three types of models from the point of view of the two attributes just described.

Models of Type 1 directly reflect what are accepted as laws of nature. Their predictive power is evident and prediction is the main purpose of their usage. These models are found rather than constructed; their validity is demonstrated by reproducible experiment. An example of this type of model is the motion of a mass point in a gravity field.

Models of Type 2 are some models in economics, sociology, biology, etc. They usually reflect theories – natural laws, if they exist, have not been found. Their predictive value is local in the mathematical sense, i.e., for points in the state space which are sufficiently far away from the initial condition, these models are sometimes quite wrong. Models of this type typically reflect macro phenomena based on the behavior of micro agents. They are validated by generating output from historical input data and comparing model outputs with the observed development of the underlying system. An example is the development of a species in a limited environment.

Models of Type 3 often have a rather simple conceptual basis entailing a rather trivial mathematical formulation (often including a large number of relations between their variables). Many relations expressed in the model are immediately plausible. An important nontrivial aspect of such a model is for example, the degree of detail incorporated, reflected by the number of relations contained in the model and by the boundary assumed for the system modeled. The predictive capability of this type of model is often irrelevant, although often overestimated. The typical point of their application is to study consequences of alternative lines of action and alternative sets of constraints to decisions. They are used to describe consistent scenarios providing a quantitative conceptualization of complex systems. Much like physical models, they help visualization of the relation between a large number of assumptions. As MESSAGE belongs to this group of models, the validation of this type of model will be discussed in more detail below. Before, some more definitions are needed.

The dynamics of the system are described by its states at time $t$. Restricting our considerations to models that are described in mathematical form, the state of a system at time $t$ is described by the value of the state variables of the model for that point in time. The state variables are therefore those variables that describe the dynamics of the system modeled. All model variables that are not state variables are control variables. They describe the control that can be applied to the state variables in order to move the system in a desired way. Using MESSAGE as an example, the capacity of, say, coal-fired power plants is a state variable which is influenced by the control variable construction of coal-fired power plants.

The system equivalent of the control variables is called system inputs. These model inputs are not to be confused with the input data to the mathematical model (the computer code representing it).* The difference between the two is easily seen in the example

$$0 \leqslant u(t) \leqslant 1$$

in which the control variable $u(t)$ is the representation of a system input whereas the parameters defining the lower and upper bounds are input data to the model.

In addition, it is helpful to further classify the input data to the computer program (representing the model) in the following way:

- Data that should be considered part of the model because they refer to system boundaries and to the degree of detail of the description of the system, e.g., the number and the names of energy demand sectors.
- Data constraining the system inputs (control variables) and system outputs, e.g., the amounts of resources available over the model time horizon.
- Model parameters, a part of the internal description, also called the "wiring diagram" in a "black-box" description (Casti 1980) of a system, e.g., the thermal efficiencies of power plants.

These groups should not be taken as an unambiguous classification but as a summary of the most important characterizations of data. In the context of this section, they are ranked in ascending order according to the degree to which they can be wrong. This means that data in the first group deal with the amount of detail that is to be incorporated in a model run and that they are therefore based mainly on judgment, whereas the last group of data refers to observations of the real system being based more on objective facts.

By system outputs we understand the real-world equivalents of the mathematically described model outputs.

Now, we turn to the validation of Type-3 models. Along with an overestimation of their predictive capabilities often goes an inadequate demand for their validation. A distinction should be drawn between forecasts and scenarios. The emphasis of a forecast is on the description of a single future development (with only statistical deviations) of the underlying system; scenarios (the result of Type-3 models), on the other hand, draw a consistent picture of the consequences of a given set of assumptions, the probability of which is not necessarily being assessed. As a consequence, a single result of Type-3 models is always much less relevant than comparisons between several model runs which typically attempt to investigate the influence of (unknown) input parameters on the model solution. Validating such a model therefore means demonstrating that the mapping from the set of assumptions onto the set of consequences is done correctly by the model. However, the question of correctness cannot be answered by yes or no. Rather, all an answer can reasonably give is the degree to which the mapping is correct. Since there is no established scale by which this degree can be measured, the answer can be given only in qualitative terms.

*For the sequel it will be assumed that, as is the case for MESSAGE, there is a computer program that corresponds to a model.

Turning to the validation of MESSAGE, the correctness of the mapping done by the model depends on the degree of simplification of a model run.* This degree of simplification is defined by the model formulation as described below *and* by the input data for a particular model run. Hence, validation of MESSAGE in the framework of this report means discussing – in qualitative terms – the degree of simplification which is implied by the very formulation of the model relations. The reader can then judge whether he agrees that MESSAGE is valid enough for its application within the global model or not.

To aid understanding a transparent presentation of the model relations was aimed at. One means to achieve this was the style chosen for the model description, consisting in a standardized formulation of dynamical LP models (Propoi 1977) for describing the model relations. One important advantage of this formulation is that it differentiates LP variables into state variables and control variables as well as distinguishing between constraints that are state equations and actual constraints. The mere separation of these terms significantly helps comprehension of the model dynamics.

The second part of the model validation, the discussion of the simplification of the mapping as defined by the input data, belongs to the data documentation and is therefore contained in Schrattenholzer (1982a). Here, we conclude these general considerations of model validation by emphasizing an important practical part of model validation – the repeated model runs. These can provide a judgmental check of the model output for reasonableness. However, this does not mean that any results that seem unreasonable point to an invalid part of the model. They may equally well reveal an important point in the system dynamics that had been overlooked. To differentiate between these two kinds of "unreasonable" results, the model user traces the input data through the model to see which model part causes the particular result.

## 3.3 Model Description

This section describes the general form of MESSAGE. To give an adequate description of a particular model run, the general outlines must be supplemented by the input data for the particular runs. In cases where it helps to understand the general equations, some of the input parameters are denoted by the values that were used in the global analysis. Further input data for the seven IIASA world regions are summarized in Appendix A. For a full documentation of all input data used in the global scenarios, see Schrattenholzer (1982a).

### *3.3.1 General Model Description*

This description is as follows. The generic form of the model relations (i.e., functions, constraints, equations) will be aggregated into groups and written down in matrix/vector notation. Each group of relations is described in a separate subsection. The grouping of model relations follows a standardized formulation of a Dynamic Linear Program (DLP) as defined in Propoi (1977) and summarized in Appendix B.

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*This is assuming that the corresponding computer program is correct, i.e., exactly generating the mathematical formulation of the model. Although, in practice, this is not a trivial aspect, for the theoretical description here we make this assumption.

Each group of relations will be followed by an explanation of those symbols that have not previously been introduced. The relations will be interpreted where not readily clear. Next, a description of the input requirements for this group of relations will be given. The last paragraph of each subsection contains a discussion of their relevance in the theoretical terms described in Section 3.2. These final paragraphs are not relevant for those readers that omitted that section.

For the formulation of the dynamic equations, the time horizon of the model is divided into $n$ time intervals of equal length. These time intervals lie between the grid points $t_0, \ldots, t_n$. In the runs for our global scenarios, the number of time periods was chosen to be 11, each one containing 5 years. Although these numbers are not fixed for the computer program corresponding to MESSAGE, they will – for the sake of clarity of the description – be treated as if they were fixed. This remark is valid for some other model parameters, too. In cases where it matters for the scenario runs, these parameters will be identified.

*3.3.2 Demand/Supply Balance*

$$\mathbf{D}x(t) \geqslant d(t) + \mathbf{H}x(t) \qquad t = 1, \ldots, 11 \tag{1}$$

where

**D** is the matrix describing supply/demand paths (constants)
$x$ is the vector of annual supply activities (control variables)
$t$ is the index of the current time period
$d$ is the vector of annual secondary energy demand (exogenous inputs)
**H** is the matrix with the coefficients for the inputs of secondary energy required by technologies (constants)

This group of constraints links the output of energy conversion technologies to the vector of exogenously given energy demand. The matrix **D** contains ones, if a technology contributes to the supply of a demand sector,* and zeroes where a technology does not contribute to the supply of a demand sector. For the sake of clarity, the matrix **H**, which defines inputs of secondary energy into conversion technologies (and thereby increases the exogenously given demand within the model), is defined separately from the matrix **D**. (As they have the same dimensions, they could have been added into one matrix which would have to be interpreted accordingly.) It should be noted here that the consideration of demand for secondary energy is a consequence of the model application. There is no implication by the model formulation that the modeling of the energy chain has to stop at the level of secondary energy. If desired, the energy chain could be considered until its end (i.e., end-use of energy) using the same general model. In that case, the demand vector contains secondary energy carriers (e.g., electricity) and end-use sectors (e.g., space heating). The only demand sectors for which demand is exogenously specified are then the end-use sectors. Demand for secondary energy is then calculated endogenously via the intermediate demand of the technologies supplying end use, expressed by the matrix **H**.

*In some cases the output $x_i$ of a technology may be defined in different units than the demand $d_j$; then, the respective matrix coefficient is the applicable conversion factor rather than unity.

Input data for this group of constraints describe the conversion factors of technologies (**D**), input requirements that consist of secondary fuels (**H**), and the energy demand projection ($d$). A demand sector can be divided into load regions (see Subsection 3.3.3).

These constraints set a lower limit to the variables $x$ which are control variables. These lower limits are exogenous and can safely be called driving parameters of the model.

*3.3.3 Capacity Utilization*

$$\mathbf{B}_1 x(t) \leqslant c(t) \qquad t = 1, \ldots, 11$$

$$\mathbf{B}_n x(t) \leqslant c(t) \tag{2}$$

where

$\mathbf{B}_i$ are the matrices defining load regions and availability of technologies in the load regions; $i = 1, \ldots, n$ (input data)
$c$ is the vector of installed capacities (state variables)

Since this form of the utilization constraints is not very instructive, they will be derived using the example of an ordered load curve of electricity demand and three load regions. The general case is then easily seen by analogy.

The upper part of Figure 2 shows an ordered load curve for electricity demand. This curve is approximated by a step function consisting of three steps. The load duration (width) of each step is optional and is part of the model input data. It should be chosen so as to "optimally" approximate the given load curve. The height of the step is determined so that the areas under the load curve and its approximation are identical. The supply activities (the vector $x$) for those technologies which supply electricity are disaggregated according to the load durations as shown in the lower part of Figure 2. In this graph the upper horizontal line represents the installed capacity, the dashed horizontal line represents the upper limit of the actual utilization of a power plant, determined by the plant factor.

Thus, for the $j$-th step of the demand curve, the capacity constraint for a given load region and for a given technology (now in scalar notation) is

$$x_{i,j}(t) \leqslant c_i(t) \cdot (h_j - h_{j-1}) \cdot pf_i \qquad t = 1, \ldots, 11 \tag{3}$$

where

$i$ is the index of the technology
$pf_i$ is the maximal plant factor, expressed as a fraction of installed capacity of the technology
$(h_j - h_{j-1})$ is the duration of the $j$-th load region ($h_0 = 0$)

In order to be able to express all these constraints in the form of eqn. (2), the constraints of eqn. (3) were divided by the constant factors of the right-hand side.

A few remarks are in order. This definition of a load region differs from the usual definition, in which a load region is defined as the area under a function of utilization

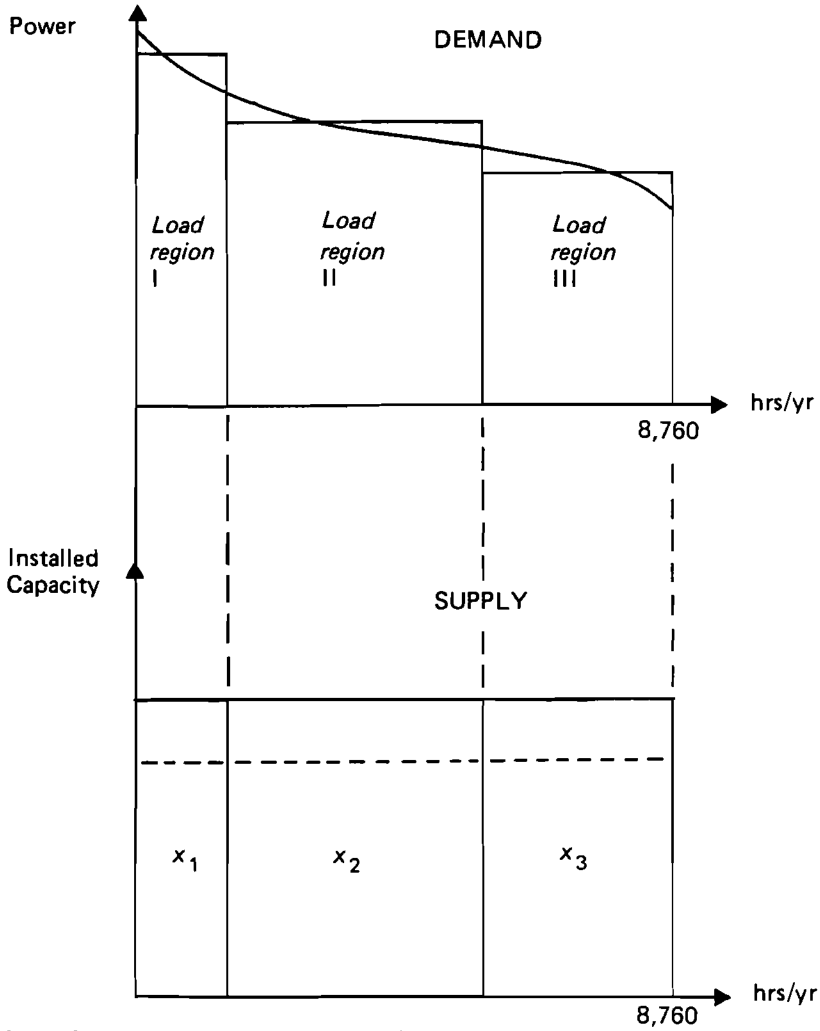


FIGURE 2 Disaggregation of supply activities.

hours per year. (In Figure 2 the usual definition would be represented by a horizontal division of the total area.) This difference is not drastic because the model solution allows results to be shown in terms of either definition. The advantage of our formulation is that it is more flexible for example, permitting variable load durations of technologies and endogenous adjustments of the demand load curve.

Input data required for these constraints are the durations of the load regions $(h_j - h_{j-1})$ and the maximal plant factors of the technologies $(pf_i)$.

These constraints are constraints on control variables by state variables. The fact that the formulation of the model assumes that the usage of a load region can be chosen by the model seems to be in conflict with reality, where technical properties of power plants put constraints on their usability in the load regions. However, this formulation was preferred because some of the technologies included in the model will only be developed in the future. For these technologies the model results provide criteria for the design of these power plants. The drawback of such freedom of the model – it can yield technically infeasible solutions – is compensated by the possibility of restricting the use of technologies to certain load regions. Details about the implementation of these restrictions in the MESSAGE computer program are found in Schrattenholzer (1982b).

### *3.3.4 Capacities of Technologies*

$$c(t) = c(t-1) + 5z(t) - 5z(t-6) \qquad t = 1, \ldots, 11 \tag{4}$$

where

- $z$ is the vector of annual additions to capacity (control variables)
- $t-6$ reflects a 30-year service life: after 6 (variable in the program, but fixed here) periods of service, an energy conversion facility is phased out

Input data belonging to this group of equations are a list of technologies (defining the length of the vectors $c$ and $z$), their initial capacities $c(0)$, and the historical construction rates $[z(t-6)$ for $t-6 \leqslant 0]$ as initial conditions.

These equations are state equations. They relate the variables $c$ (state variables) to the variables $z$ (control variables). Since the single $z$-variables can take any nonnegative value, this means that the size of installed energy conversion facilities can be arbitrarily small. Because of the large size of the geographical regions modeled and because of the large time horizon, this did not pose a problem in the global analysis. If the model is applied to smaller geographical regions or for shorter time spans, this point must be kept in mind.

### *3.3.5 Build-Up Constraints*

$$z(t) \leqslant \gamma z(t-1) + g \qquad t = 1, \ldots, 11 \tag{5}$$

where

- $\gamma$ is a (diagonal) matrix of growth parameters (input data)
- $g$ is a vector of start-up values allowing $z$ to reach positive values after having been zero before (input data)

$$\sum_{i \in I_1} z_i(t) \leqslant GUB(t) \qquad t = 1, \ldots, 11 \tag{6}$$

where

- $GUB(t)$ is a time series of absolute upper limits (input data)
- $I_1$ is a subset of the set of technologies

The first group of constraints limits the growth rates of build-ups of single technologies, the second one puts an absolute upper limit on the total installation of a group of technologies. The first group is particularly important for new technologies. the second group is so far only used for limiting the total annual installation of nuclear capacity.

Input data are the growth parameters ($\gamma_{i,i}$) of the first group of constraints and the time series of installation limits [$GUB(t)$] for the second.

The functioning of eqn. (5) can be illustrated for the case of a new technology, for which these constraints are binding for some time periods, $t_i$, $t_{i+1}$, etc. In this case, total installed capacity of this technology is proportional to the parameter $g$ and roughly proportional to $\gamma_{i,i}^n$ where $n$ is the number of time periods in which the constraint is binding.

The build-up constraints just constrain the control space making sure that some foresight is employed by the model – the need for technology in the future is anticipated early enough, keeping growth rates within limits. This function is not the only reason why these constraints are to be considered to belong to the most important ones of the model. Another reason is suggested by Marchetti and Nakićenović (1979), where the penetrations of new energy carriers into existing energy systems are investigated. There, many examples are given and a theory is described that support the conjecture that such penetrations follow internal laws. In MESSAGE, a less constraining form of such a law, an inequality instead of an equality, has been incorporated.

### *3.3.6 Resource Balances*

$$s(t) = s(t-1) - 5r(t) \qquad t = 1, \ldots, 11 \tag{7}$$

where

- $s$ is the vector of reserves (stocks) of primary energy carriers or man-made fuels (state variables)
- $r$ is the vector of annual consumption of primary energy carriers (control variables)

The lengths of the vectors $s$ and $r$ depend on the number of natural and man-made resources incorporated in the model. These resources can be subdivided into different cost categories in which case the vectors $s$ and $r$ are extended accordingly. Such a disaggregation can be interpreted as an approximation of the nonlinear relation between the availability and the unit cost of a resource by a step function.

Input data belonging to this group of constraints are the total resource availabilities $s(0)$. It is worth remembering here that LP variables are nonnegative by default. This is an important constraint for the vector $s$ making sure that not more than the initial availabilities $s(0)$ are consumed in the model. For those activities in the vector $r$ that refer to man-made fuels, this nonnegativity constraint is removed so as to also allow for production (not only consumption) of these materials.

Renewable energy sources (solar, hydro, etc.) are not included in these constraints as their total availability is unlimited for the purpose of the model. However, the *rate* of utilization of renewable sources is limited. This limitation is introduced as the characteristic of a technology converting renewable energy and is described in Subsection 3.3.9 where the bounds of the model variables are discussed.

Eqn. (7) is a state equation relating annual consumption of primary energy $r$ (control variables) to the total stock of primary energy $s$ (state variables). An implicit assumption behind this formulation is that any share of available resources can be used at any time within the time horizon and thus arbitrarily fast. This is in contrast to the real world, where a good part of the resources used in a given time interval of 50 years are only gradually discovered or deployed. However, MESSAGE contains a means for compensating this drawback to some extent as the model formulation allows the limitation of annual production of primary energy. These constraints are described below.

### *3.3.7 Resource Consumption*

$$\mathbf{G}r(t) \geqslant \mathbf{Q}_1 x(t) + \mathbf{Q}_2 z(t) - \mathbf{Q}_3 z(t-6) \qquad t = 1, \ldots, 11 \tag{8}$$

where

- **G** is a binary matrix (containing only zeroes and ones) aggregating all categories of a resource (input data)
- $\mathbf{Q}_1$, $\mathbf{Q}_2$, and $\mathbf{Q}_3$ are matrices of parameters describing specific consumption of resources by conversion technologies (model input data belonging to the definition of technologies)

As mentioned above, resources can be divided into different cost categories. Since they are nevertheless meant to serve the same purpose, these categories are aggregated, by the matrix **G**, when balanced with the resource consumption of the energy conversion facilities. This consumption is expressed by the matrices $\mathbf{Q}_1$, $\mathbf{Q}_2$, and $\mathbf{Q}_3$ which describe resource consumption per unit of output ($\mathbf{Q}_1$), per unit of new capacity ($\mathbf{Q}_2$), and recovery of a resource at the end of a service life of a technology ($\mathbf{Q}_3$). For the time being, $\mathbf{Q}_2$ and $\mathbf{Q}_3$ are exclusively used to describe inventory requirement and recovery of nuclear fuels.

Input data for these constraints are the specific consumption of fuels (matrices $\mathbf{Q}_i$) and the disaggregation of resources into categories (matrix **G**).

As already pointed out, the disaggregation of resources into cost categories and their subsequent aggregation for the purpose of their consumption can be interpreted as a nonlinear cost function for a resource. The way the model is set up, the independent variable in this function is cumulative use of a resource. An alternative formulation would be to have such a function depend on the use of a resource in each time period, in which case the model could determine the cost level up to which it is optimal to deploy a resource. Such a formulation seems to be more realistic but at the same time more data intensive. This trade-off has been resolved in favor of using the above formulation. The linearity of the right-hand side of the above relation assumes a linear relationship between fuel input and energy output for the energy conversion facilities. This simplification was considered appropriate for the applications carried out so far.

### *3.3.8 Resource Extraction*

$$\mathbf{G}_1 r(t) \leqslant p(t) \qquad t = 1, \ldots, 11 \tag{9}$$

where

$\mathbf{G}_1$ is the matrix for the aggregation of indigenous resource categories (input data)
$p$ is the vector of annual production limits for each resource kind (exogenous inputs)

Optionally, one category per resource may be defined as import category. (Since there can be at most one import category for each resource, the costs of import categories may be defined to be time dependent. See also the description of the objective function.) Such a definition does not change the purpose of its use as a resource as described in eqn. (8). The separate definition of an import category applies in this group of constraints, where the total annual extraction of only indigenous resource categories is constrained. The annual amount available for the import of any resource is constrained separately as described in Subsection 3.3.9.

Input data required for these constraints are time series of upper limits for the annual extraction of indigenous resources $[p(t)]$.

This group of constraints sets an upper limit to a part of the control variables $\boldsymbol{r}$. The way these constraints are formulated assumes that each cost category of a particular resource can be exploited up to its maximum availability before the next category is tapped. In the LP solution this is reflected by abrupt transition between adjacent categories. It may be argued that for example, a separate bound on each category for each time period would be more realistic because depletion rates of resource categories could be taken into account thus allowing for smoother transitions between categories. At the same time, such a formulation would be one way to approximate the nonlinear cost function for a resource for each time period rather than over the time horizon . Because of these advantages, the decision to choose this particular formulation was very close, just slightly in favor of the decision finally taken.

*3.3.9 Bounds on Single Variables*

Since bounds on single variables in many LP computer packages are taken together in one set, they are treated here under one heading; and since the mathematical formulation is too trivial to add any further information, only a qualitative description is given.

Lower, upper, or fixed bounds may be set on the supply of a single technology ($\boldsymbol{x}$-variables) and on the installation of new capacity ($z$-variables). Bounds on $\boldsymbol{x}$-variables are usually used to limit the harvesting of renewable energy sources; bounds on $z$-variables are a means to constrain capacities of technologies also in absolute terms (not only their growth as described in Subsection 3.3.5). Upper bounds may be set on the annual availability of an import resource category. The treatment of renewable energy in MESSAGE deserves some further explanation. As is the case for nonrenewable energy, increasing utilization, in general, entails increasing unit costs. This is usually taken into account in the model, by defining two (or more) technologies that have the same technical characteristics but different costs. Bounds are then set for the output of these technologies (the corresponding $x$-variables) making sure that the model cannot choose more of a technology than that available at a certain cost.

Input data to this part of the model are the kinds of bounds (lower, upper, fixed) and the corresponding time series.

Although the practical relevance of the bounds is trivial, the fact that these bounds constrain the control space of the modeled system and thus significantly influence the model output, makes the bounds a characteristic ingredient of Type-3 models and thus of MESSAGE.

### *3.3.10 Objective Function*

$$\sum_{t=1}^{11} \beta_1(t)(a_1 x(t)) + \beta_2(t)(a_2 z(t)) + \beta_1(t)(a_3(t), r(t)) \to \min \tag{10}$$

where

$\beta_i$ are discount factors (input data)
$a_i$ are vectors of annual cost coefficients (input data)

Because of the special formulation of eqns. (2) and (4), which imply that the annual utilization of a capacity already includes the build-up in the same time period, the build-up variables $z$ have to be interpreted as activities occurring before the supply activities $x$ which utilize this capacity. Consequently, the discount factors belonging to the respective LP variables have to be different to take account of this time lag. Besides the time lag, all the discount factors $\beta_i(t)$ are uniformly calculated using constant annual discount rates. In addition, the parameters $\beta_2(t)$ contain a correction factor expressing the value of capacity that keeps operating beyond the model time horizon. Thus the objective function excludes costs, the benefits of which do not accrue within the model boundaries. The cost coefficients are – with the exception of the costs for an import resource category – constant over time, the usual interpretation being that the costs remain constant in real terms. Accordingly, the discount factors are interpreted as real discount factors excluding inflation. An expected change of costs of technologies can be reflected in the model by defining two model technologies with different costs and different availabilities over time.

The input data belonging to the objective function are the annual discount rate and the cost coefficients.

Taking costs as the function to be minimized assumes economically rational behavior of future decision makers. Although it is implied in what has been said already, it should be pointed out here that this formulation of the objective function does not mean that costs are the only criterion determining the model output. Other criteria are imposed by the model constraints. (Subsection 3.3.12 on the environmental submodule of MESSAGE introduces still another criterion.) Also it is repeated here that in the applications for the global runs the location of the feasible region in the state space, determined by the scenario variables, has always had a larger effect on the solution than the optimal point in the state space, determined by the objective function. Nevertheless, some model features based on this function will be discussed in more detail.

One important drawback of an LP model – in the case of uncertain input data – is the discontinuous dependence of the solution on the objective function: a small change in cost data can eliminate a technology's contribution to energy supply replacing it by a different one. Thus, if no consideration is given to this feature, a "second-best" solution can remain undiscovered although it would be optimal under an only slightly different objective function. Usually, this problem is solved by analyzing the model sensitivity. However, the sensitivity analysis depends on the model application much more than on the model itself and therefore falls outside the scope of this report. The particular form of sensitivity analysis that was thought to be appropriate for the global analysis is described in Energy Systems Program Group (1981). A related problem is the sudden replacement of one energy source by another as soon as a "cheaper" one becomes available. MESSAGE contains two features that limit this unsteady behavior of the solution: the build-up constraints for technologies prevent sudden build-up of a technology; and the explicit consideration of capacities the underutilization of which entails economic penalty thus working against a sudden drop-out of a technology.

### *3.3.11 Initial Conditions*

The initial conditions have already been described together with the corresponding variables. Here, they are summarized under a common heading.

The initial capacities $c(0)$, and the historical build-up activities $z(0), \ldots, (z-5)$ of all technologies have to be specified consistent with the conditions

$$c(0) = z(0) + \ldots + z(-5)$$

and

$$z(t) \geqslant 0, \qquad t = 0, \ldots, -5 \tag{11}$$

The only other set of initial conditions are the numbers of the availabilities of natural resources, which in fact are an upper limit on the amount of resource which is available in a category within the time horizon of the model.

The theoretical relevance of the initial conditions for MESSAGE does not seem to justify separate discussion. (The initial conditions are much more critical for the evolution of the system for those types of models in which control plays a lesser role.)

### *3.3.12 Environmental Submodule*

The environmental impact is one of the most intensively discussed aspects of energy supply strategies. Along with widespread discussion goes a large number of vastly different views of various impacts, expressed by significant differences in the corresponding data. Taking these discrepancies into account would have meant performing a considerable number of model runs in order to match the technical and economic parts of the global energy scenarios with an adequate scenario on environmental impacts. Even an extended study in this respect would have carried the risk of being inconclusive. In view of these difficulties the two global energy scenarios restrict the consideration of the environmental impact of energy supply strategies to one global kind of impact – the global $CO_2$ concentration in the atmosphere. With respect to the importance of the environmental impact, the corresponding part of MESSAGE is somewhat elaborate, allowing for a more thorough treatment of this problem than in the global study.

As it describes a part of the model which was only used to some extent in the description of the global scenarios, this subsection on the environmental submodule of MESSAGE is separated from the rest of the model description. Although this somewhat breaks the format it does summarize related parts of the model in one place.

The following two equations are the basis for the environmental submodule:

$$e(t) = \mathbf{E}x(t) \qquad t = 1, \ldots, 11 \tag{12}$$

where

$e$ is the vector of emissions of pollutants (state variables)
$\mathbf{E}$ is the matrix of specific emissions (input data)

$$b(t) = \lambda(-t)b(0) + \sum_{\tau=1}^{t} 5\lambda(\tau - t)e(\tau) \qquad t = 1, \ldots, 11 \tag{13}$$

where

$b$ is the vector of concentration of pollutants (state variables)
$\lambda$ is a (diagonal) matrix of coefficients expressing the rest time of pollutants in the environment (input data)

These two groups of equations account for emissions of pollutants [eqn. (12)] and ambient concentrations of selected pollutants [eqn. (13)]. There are three levels at which these variables can be used within MESSAGE. Firstly, they may be used as monitoring variables only. In this case, they merely quantify the environmental impact of an energy supply strategy in natural units. Secondly, these variables may be constrained thus reflecting emission or concentration standards in the model. Finally, they may be included in the objective function thus directly participating in the optimization. The last of these three levels can be interpreted as multiobjective optimization. An example of such a joint optimization of economic and environmental aspects in a mathematical programming model is found in Jansen (1977).

Input data requirements for the environmental submodule of MESSAGE depend on the extent to which it is used for a particular model run. If it is fully used, the data required are on specific emissions of pollutants by energy conversion facilities, rest times of pollutants, the initial concentrations of pollutants, emission and concentration standards, and "cost data" (objective function coefficients) for emission and concentration variables.

The formal relevance of the emission and concentration variables is an extension of the state space of the model and the corresponding description of the results in these terms. Constraining the range of these variables means a reduction of the feasible region; their inclusion into the performance index means a change in the preference ranking of the energy conversion alternatives. As far as the inclusion in the objective function is concerned, it should be noted that the assumption of linearity means rather oversimplifying the real-world system.

## 4 EXPERIENCE AND CONCLUSIONS

MESSAGE was developed for the application to geographical regions the size of continents. It may also be applied to smaller regions or countries, provided that some care is taken in supplying the input data and in interpreting the model results. A particular problem that may arise comes from the continuity of the model variables that – for small countries – may very likely result in sizes of energy conversion facilities that are unrealistically small. Also, in some regions or countries the energy system may have some peculiarities which have not been considered in the general model formulation.

Both problems appeared in applying the model to Austria, because of her small size and her heavy reliance on hydro storage. The results of this application showed that the difficulty of continuous variables was less serious than might have been expected. Even continuous solutions yielded a good enough first set of scenarios (Schrattenholzer 1979). The continuous solutions were then adjusted by trial and error to arrive at reasonable block sizes of power plants. This method was considered preferable to using mixed integer programming, a method similar to linear programming, but permitting restriction of variables to discrete values. The difficulty relating to Austria's heavy reliance on hydro storage was solved by a modification of the original model.

Another important application of MESSAGE besides its usage within the global model was the one for the Commission of the European Communities (CEC). In contrast to the application for Austria, where the emphasis was on the transfer of methodology, the CEC application emphasized the disaggregation of global results. This was achieved by splitting IIASA's Region III into "Europe of the Nine" and "Rest of the Region" using a modified model loop. The results of the IIASA models were then compared with "bottom-up" model runs performed by the CEC. A description of this work contrasting regional aspirations with globally consistent scenarios, is contained in Commission of the European Communities (1980).

Other applications underway (such as for Brazil, Bulgaria, the FRG, and Hungary) seem to prove that the definition of MESSAGE is general enough to serve as a basis for a great variety of applications.

Work is currently being undertaken at IIASA to extend MESSAGE. The extensions are the result of modeling the energy chain up to useful energy, of running the model for a longer time period, and of modeling countries for which detailed data are available. The extended model is called MESSAGE II and is documented in Messner (1982).

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## APPENDIX A

This appendix defines the seven world regions and presents some high-level input data for these regions, giving some idea of the model boundaries of the MESSAGE runs for the global scenarios.

The seven world regions are:

*Region I* North America
*Region II* Soviet Union and Eastern Europe
*Region III* Western Europe, Japan, Australia, New Zealand, South Africa, and Israel
*Region IV* Latin America
*Region V* Africa (except Northern and South Africa), South and Southeast Asia
*Region VI* Middle East and Northern Africa
*Region VII* China and Other Asian Countries with Centrally Planned Economies

The input data in this appendix give, for each region, the names of the demand sectors and the names of the technologies supplying these sectors. The list of primary energy carriers is the same for each region and will therefore be given only once (at the end of this appendix). It does not contain renewable energy sources as these are treated differently (under the description of the technologies). For complete information about all input data, the reader is referred to Schrattenholzer (1982a).

**Region I**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels
Gaseous fuels
Soft solar

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas-steam power plant
   Gas turbines
2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities

**Region II**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels

Gaseous fuels
Soft solar
Heat I
Heat II

The difference between the two heat sectors is that "Heat I" means demand for heat which can be supplied by central sources. "Heat II" is heat which can only be supplied by smaller units.

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas-steam power plant
   Gas turbines
2. Combined production of Heat I and electricity:
   Light water reactor (LWR)
   Coal-fired power plant
   Liquid fuel power plant
   Gaseous fuel power plant
3. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
4. Solid fuels:
   Coal
5. Gaseous fuels:
   Natural gas
   Coal gasification
6. Soft solar:
   Local solar energy conversion facilities
7. Heat II:
   Light water reactor (LWR)
   Coal-fired power plant
   Liquid fuel power plant
   Gaseous fuel power plant

**Region III**

*Demand sectors:*
Electricity
Liquid fuels

Solid fuels
Gaseous fuels
Soft solar
Heat

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas-steam power plant
   Gas turbines
2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities
6. Heat:
   Geothermal heat
   Combined production of heat and electricity

**Region IV**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels
Gaseous fuels
Soft solar
Heat
Renewables

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)

Coal-fired power plant
Coal-fired power plant (advanced)
Hydroelectric power plant
Hydroelectric power plant (expensive)
STEC (centralized solar power plant)
Liquid fuel power plant
Gas-steam power plant
Gas turbines

2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities
6. Heat:
   Local solar energy conversion facilities
7. Renewables:
   Fuel wood

**Region V**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels
Gaseous fuels
Soft solar
Heat
Renewables

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   Hydroelectric power plant (expensive)
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas-steam power plant
   Gas turbines

2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities
6. Heat:
   Combined production of heat and electricity

**Region VI**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels
Gaseous fuels
Soft solar
Heat

*Technologies:*
1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas-steam power plant
   Gas turbines
2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities
6. Heat:
   Combined production of heat and electricity

**Region VII**

*Demand sectors:*
Electricity
Liquid fuels
Solid fuels
Gaseous fuels
Soft solar
Heat

*Technologies:*

1. For electricity generation:
   Light water reactor (LWR)
   Fast breeder reactor (FBR)
   Coal-fired power plant
   Coal-fired power plant (advanced)
   Hydroelectric power plant
   STEC (centralized solar power plant)
   Liquid fuel power plant
   Gas turbines
2. Production of liquid fuels:
   Crude oil refinery
   Coal liquefaction
3. Solid fuels:
   Coal
4. Gaseous fuels:
   Natural gas
   Coal gasification
5. Soft solar:
   Local solar energy conversion facilities
6. Heat:
   Combined production of heat and electricity

**Resources and Fuels (Same for all Regions)**

Coal
Crude oil
Natural gas
Natural uranium
Plutonium

## APPENDIX B

This appendix gives the general definition of a dynamic linear programming (DLP) model as described in Propoi (1977) and as used in this report. In the general definition, each part of a DLP is formulated by alternative descriptions; however, the description here is restricted to only those variants that apply for MESSAGE.

*I. State equations*

$$x(t+1) = \sum_{i=1}^{\nu} A(t-n_i)x(t-n_i) + \sum_{j=1}^{\mu} B(t-m_j)u(t-m_j) \qquad t = 0, \ldots, T-1$$

where

$x$ is the vector of state variables
$u$ is the vector of control variables
A, B are matrices (model input data)

*II. Constraints*

$$G(t)x(t) + D(t)u(t) \leqslant f(t)$$

where

G, D are matrices (input data)
$f$ is a vector (input data)

*III. Boundary Conditions*

$$x(0) = x^0$$

*IV. Planning Period*

$T$ is fixed.

*V. Performance Index (Objective Function)*

$$J(u) = [a(T), x(T)] + \sum_{t=0}^{T-1} \{[a(t), x(t)] + [b(t), u(t)]\} \to \max (\min)$$

where

$a$, $b$ are vectors of cost coefficients (input data)

The variables of MESSAGE, disaggregated between state and control variables are:

Control variables:
$r(t)$ (annual consumption of resources)
$x(t)$ (energy production)
$z(t)$ (annual additions to capacity)

State variables:
$b(t)$ (concentrations of pollutants)
$c(t)$ (capacities of technologies)
$e(t)$ (annual emissions of pollutants)
$s(t)$ (stocks of resources)

# THE AUTHOR

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Dr. Schrattenholzer received his degree in Mathematics in 1973 and his Ph.D. in 1979, both from the Technical University of Vienna. His Ph.D. thesis was on modeling long-term energy supply strategies for Austria. From 1972 to 1974 he was a research and lecture assistant with the Institute of Mathematics, I, of the Technical University.

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Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 225 pp. $16.50.
Written by Jeanne Anderer with Alan McDonald and Nebojša Nakićenović

**ENERGY IN A FINITE WORLD: A GLOBAL SYSTEMS ANALYSIS**
Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 837 pp. $45.00.

Both of the above volumes are available from Ballinger Publishing Company, 17 Dunster Street, Cambridge, Massachusetts 02138, USA.

**ENERGY IN A FINITE WORLD: EXECUTIVE SUMMARY**
Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 74 pp. Written by Alan McDonald.

Free copies available from IIASA.

The other publications listed here are divided into five subject areas:

1 Global, regional, and sectoral energy models – whether for energy demand, energy supply and conversion, or for economic, resource, or environmental impacts of energy technologies.

2 The analysis of different energy sources – i.e., fossil fuels, nuclear power, solar power and other renewables – and the conversion, storage, and transportation technologies associated with them.

3 The analysis of energy demand patterns.

4 Environmental and safety risks of energy technologies.

5 The analysis of total energy systems and energy strategies including all the dimensions of the first four categories taken together.

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Books in the International Series on Applied Systems Analysis (Wiley) can be ordered from John Wiley & Sons Ltd., Baffins Lane, Chichester, Sussex PO19 2UD, United Kingdom.

Books published by Pergamon Press can be ordered from Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, United Kingdom, or Pergamon Press, Inc., Fairview Park, Elmsford, N.Y. 10523, USA.

All other publications can be ordered from the Publications Department, IIASA, A-2361 Laxenburg, Austria.

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**RR-80-31.** The IIASA Set of Energy Models: Its Design and Application. P.S. Basile. December 1980. 65 pp. $7.00

**RR-78-17.** MEDEE-2: A Model for Long-Term Energy Demand Evaluation. B. Lapillonne. November 1978. 45 pp. $6.00

**RR-79-8.** The Economic IMPACT Model. Yu.D. Kononov, A. Por. October 1979. 72 pp. $8.50

A Long-Term Macroeconomic Equilibrium Model for the European Community. H.H. Rogner. 1982. (Forthcoming Research Report.)

A Long-Term Macroeconomic Equilibrium Model for the European Community. H.H. Rogner. 1981. (Forthcoming Research Report.)

Modeling of Large-Scale Energy Systems. Proceedings of the IIASA–IFAC Symposium on Modeling of Large-Scale Energy Systems. W. Häfele, Editor, L.K. Kirchmayer, Associate Editor. 1981. 462 pp. (Available from Pergamon Press.) $72.00

**CP-74-3.** Proceedings of IIASA Working Seminar on Energy Modeling, May 28–29, 1974. May 1974. 342 pp. $13.00

**RR-74-10.** A Review of Energy Models: No. 1 – May 1974. J.-P. Charpentier, Editor. July 1974. 102 pp. $8.50

**RR-75-35.** A Review of Energy Models: No. 2 – July 1975. J.-P. Charpentier, Editor. October 1975. 133 pp. $10.00

**RR-76-18.** A Review of Energy Models: No. 3 (Special Issue on Soviet Models). J.-M. Beaujean, J.-P. Charpentier, Editors. December 1976. 33 pp. $4.00

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North Sea Oil. Resource Requirements for Development of the U.K. Sector. J.K. Klitz. 1980. 260 pp. (Available from Pergamon Press.) $36.00

Future Supply of Nature-Made Petroleum and Gas. R. Meyer, Editor. IIASA, UNITAR. 1977. 1046 pp. (Available from Pergamon Press.) Hard cover $60.00, soft cover $40.00

Conventional and Unconventional World Gas Resources. M. Grenon, C. Delahaye, Editors. 1981. (Forthcoming from Pergamon Press.)

Future Coal Supply for the World Energy Balance. M. Grenon, Editor. 1979. 720 pp. (Available from Pergamon Press.) $90.00

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## 3. Energy Demand

Evolution of Future Energy Demand Till 2030 in Different World Regions: An Assessment Made for the Two IIASA Scenarios. A.M. Khan, A. Hölzl. 1982. (Forthcoming Research Report.)

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Climate and Energy Systems. J. Jäger. 1981. (Forthcoming.)

Climatic Constraints and Human Activities. Task Force on the Nature of Climate and Society Research, February 4–6, 1980. J. H. Ausubel, A.K. Biswas, Editors. 1980. 214 pp. (Available from Pergamon Press.) $30.00

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