A MODEL FOR ENERGY SUPPLY SYSTEMS ALTERNATIVES AND THEIR GENERAL ENVIRONMENTAL IMPACT

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PREFACE

IIASA's Energy Systems Program is directed towards global and long-term aspects of the energy problem, especially those problems arising from the transition from energy supply systems based on fossil fuel resources to one based on resources capable of supplying large amounts of energy more or less indefinitely. The Energy Systems Program is making several detailed studies of major options for supplying energy on a large scale, such as nuclear, solar and coal. It is recognised, however, that one major option alone may not be sufficient to supply all the energy that will be required and that other constraints, apart from the availability of raw energy resources, may be crucial in making the transition smoothly. These constraints are imposed by the socioeconomic system and by the environment. Recognising the system nature of the energy problem, a set of models has been developed within the Energy Systems Program to provide a comprehensive and consistent framework with which to examine the central findings of the individual studies.

The description which follows is a statement of the mathematical structure of one of the central building stones of the modelling effort, namely MESSAGE: a model for energy supply systems and their general environmental impact. MESSAGE is a dynamic linear programme which allocates energy conversion processes to transform raw energy resources into a form suitable for final demand.

The results of model runs will be presented in a number of other reports dealing with individual world regions and specific problems.

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SUMMARY

The overall objective of the energy strategies modelling effort within the IIASA's Energy Systems Program is to construct a set of multiregional models of the world to assist in the analysis and evaluation of regional and global energy strategies for the next 15 to 50 years.

The energy system of each world region is characterised by a set of interrelated models each dealing with a different aspect of energy systems analysis. These include models of

- the macroeconomy;
- inter-industry product flows;
- energy demand;
- primary energy resources;
- energy supply technologies and their environmental impact; and of
- the direct and indirect investment and operational requirements of energy systems.

A global balance model of interregional trade in energy resources is under preparation for linking the set of regional models together.

The present paper is concerned with item 5 above, namely the model MESSAGE, a Model for Energy Supply System Alternatives and Their General Environmental Impact. MESSAGE is formulated as a dynamic linear programme for the comparison of new and existing supply technologies for the primary, secondary and end-use conversion and distribution of energy to satisfy each of the different components of a given energy demand. Constraints are imposed by the availability of primary energy resources and the carrying capacity of the environment.

MESSAGE is an instrument designed to compare different energy supply and end-use technologies and to explore the

consequences of pursuing a wide range of possible energy supply strategies under various assumptions concerning

- the availability of primary energy supply;
- future energy conversion technologies;
- different levels of energy demand and end-use patterns;
- environmental control; and
- conservation of energy.

The purpose of MESSAGE in particular, and of the modelling effort of the Energy Systems Program in general, is not to make predictions or forecasts but to clarify some of the major worldwide consequences of taking alternative energy policy choices at the regional and global levels.

Although the model described here was conceived as an integral part of the multiregional energy study of the Energy Systems Program, it is a consistent entity which could be used independently of the other models in evaluating the energy supply strategies of individual nations.

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A Model for Energy Supply Systems Alternatives and Their General Environmental Impact

1 INTRODUCTION

1.1 IIASA's multiregional evaluation of energy strategies

The expected increases in demand for energy and the inevitable increase in the discharges of residuals associated with its supply, the depletion of traditional reserves of primary energy resources and the intensified capital requirements of new energy supply technologies focus our interest on the need for a planning instrument or model forming a consistent and comprehensive framework for analyzing alternative energy systems and their impact on society and the environment. This is the setting for the energy modelling effort of IIASA's Energy Systems Program which is directed at medium- to long-term (15 to 50 years) aspects of the global energy problem.

The main objectives are to develop a consistant set of methods and procedures for

- comparing global energy options and
- evaluating regional [1] energy strategies or policies in view of global and regional constraints.

The structure of the model approach is given as follows: The world is divided into a small number of regions (between six and ten) reflecting socio-economic and political homogenity and geographic location. The energy system of each region is characterised by a set of models

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[1] The word "region" is used in the special sense to mean a "world region", such as North America or Western Europe, and usually comprises a number of political states. But the word "region" is not a substitute for "continent" since a region is required to be more or less homogeneous on a socio-economic and political basis and is not necessarily, but desirably, geographically contiguous. Thus "regional strategy" also has a special meaning of being the aggregate "strategy" of individual states.

relating to different aspects of the energy problem. A global balance model, using a gaming approach to model interregional trade in energy resources, is being prepared to link each set of regional models.

The "family" of models used to characterise each region's energy system comprises

1 A <u>macroeconomic model</u> describes the long-term development of the economic structure and simulates the evolution of aggregate economic indicators, such as gross national product and capital investment, over the next 50 years.

2 An <u>input/output model</u>, which takes its exogenous input from the macroeconomic model, ensures internal consistency of operation among various production sectors in the modelling scheme and provides information on the development of various industrial sectors in particular and economic growth in general.

3 An <u>energy demand model</u>, which uses the output of the macroeconomic and input/output models but also takes account of the climate of the region, the life-style of the population the industrial structure of the economy and the technical efficiences of energy end-use, is used to estimate the component parts of future energy demand.

4 A <u>resource model</u> sets out for each region estimates of the reserves that could be exploited at various cost[2] levels, location and quality, taking account of probable future resource discoveries.

5 An <u>energy supply and environmental impact model</u> which compares alternative technological systems for the primary and secondary conversion, distribution and end-use of energy in order to satisfy each of the different components of a given useful energy demand. Exogenous input is given by the resource model (item 4) and the demand model (item 3).

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[2] The word "cost" rather than "price" is used deliberately. Although measured in monetary units, it is a surrogate for inputs of labour, materials and capital rather than for market price.

6 An economic impact model which (a) identifies the direct and indirect investment and operational requirements of a given energy strategy and (b) examines what restructuring of the economy might be necessary.

The relations between these models are shown schematically in Figure 1. An iterative solution of the set of models is clearly implied both between and within regions.

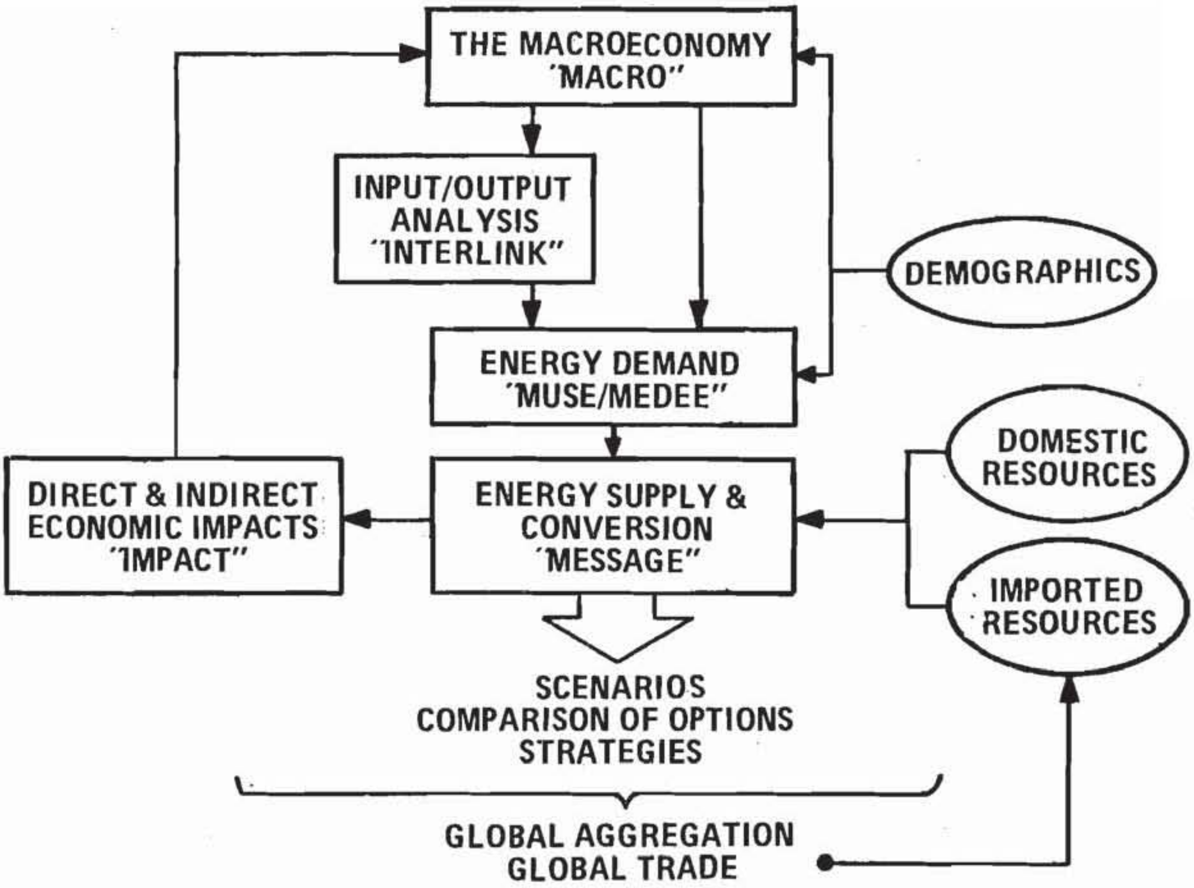

Figure 1 A profile of the IIASA set of energy models for a region

1.2 The energy supply system

MESSAGE, the subject of the rest of this paper, is a dynamic linear programme for comparing alternative existing and new energy supply technologies for the primary and secondary conversion, distribution and end-use of energy in order to satisfy each of the different components of a given useful energy demand. Constraints are imposed by the availability of primary energy resources at various cost levels and by the carrying capacity of the environment. Additional constraints impose limits on the speed of market penetration of new technologies and the rate of decline of existing technologies where this rate of decline might pose social problems. MESSAGE finds a cost optimal solution for achieving a smooth transition from an energy system based on scarce fossil resources to one that is based on primary energy resources and that is capable of supplying very large amounts of energy more or less indefinitely. But it can also be used, for example, to explore the consequences of imposing more stringent controls on the level of environmental impact of the energy supply system or to examine the potential of new technologies to find out at what cost structure they become competitive.

Most models have family connections. The grandfather of MESSAGE was the Häfele/Manne model [1] and a number of brothers and sisters exist at IIASA [2,3]. The present version is more ambitious than its predecessors, incorporating several improvements and extensions. We have grouped these extensions below under two headings, namely MESSAGE I and MESSAGE II. The first group consists of extensions that are already fully operational whereas the second group refers to extensions that are in various stages of development.[3]

MESSAGE I

- a greater number of central station supply technologies;
- the addition of an optional number (usually between three and six) of resource categories distinguishing between extraction costs and location and quality of deposits;

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[3] We will elaborate on the difference between MESSAGE I and MESSAGE II in more detail later in the paper.

- the explicit consideration of load demand curves, derived from the daily and seasonal variation of demand, for electricity, space heat and air conditioning;
- the inclusion of the possibility of variable joint production of district heat and electricity;
- the explicit consideration of price-induced conservation of energy;
- the calculation of residual discharges to the environment and the possiblity of constraining these emissions;
- the introduction of abatement technologies for reducing residual discharges;
- increased programme flexibility.

MESSAGE II

- a partitioning of the population according to population and energy density allowing for a more satisfactory treatment of end-use of energy and environmental impacts;
- the introduction of end-use technologies;
- a detailed consideration of environmental impacts.

1.3 Model objectives and limitations

During the last few years, numerous models of the energy system have been developed with widely varying objectives and based on various methodological approaches [4-8] . A good overview is given in a series of IIASA reports reviewing energy models [9-11].

Which methodological approach is finally selected is governed by the sort of questions one wishes to answer but also by the system being modelled. The supply of energy does not often occur under conditions that characterise the operation of the perfect market of the classical economists - which assumes a large number of independent actors in both supply and demand sectors. Rather the structure of the energy supply system is the result of a few crucial and far reaching decisions taken at governmental or supra-national level.

MESSAGE is concerned with the problem of allocating resources, materials and manpower to satisfy a given future energy demand without inflicting intolerable damage on man's environment. For this reason it seemed appropriate to formulate this important building stone in the multiregional energy study of IIASA's Energy Systems Program as a linear programme. Since the major concern of the study is with the medium- to long-term aspects of the energy problem, especially those related to achieving a smooth transition from present energy systems based on (relatively) cheap fossil resources to systems capable of supplying large amounts of energy more or less indefinitely, a dynamic optimisation model was constructed. For a given set of estimates of primary energy resource levels and future energy demands, and given assumptions on the availability of conversion technologies, etc., MESSAGE determines one solution which is an optimal allocation of available resources and technologies to satisfy energy demand. But the modelling process starts rather than ends with the first optimal solution. By changing the assumptions and/or the estimates, many possible energy supply alternatives can be investigated. The name of the game is not prediction but rather the exploration of alternative energy futures.

To summarise: The aim of MESSAGE is to serve as an instrument in exploring the consequences of a wide range of possible energy futures; in other words, to examine the level and timing of direct capital requirements and the environmental implications of adopting any one of a number of possible energy supply systems under varying assumptions on:

- the availability of primary energy supplies;
- present and future energy conversion technologies;
- different levels of demand and end-use patterns;
- environmental control; and
- conservation of energy;

as well as to show what decisions must be taken and when in order to implement a number of possible (or, in the terminology of linear programming, feasible) alternative energy strategies.

Each model is necessarily a much simplified reflection of the real system being simulated. It is necessary to strike a compromise between the things one would like to include in a model and the amount of research potential and data available. Since the energy system interacts with every facet of man's life the compromise is particularly difficult for energy modellers. Some hard questions must be asked on the sort of information that the model is intended to produce. Below we list some of the more important issues that MESSAGE should help to answer, followed by some of the questions which lie outside the scope of MESSAGE (but not necessarily outside the wider context of the family of models in IIASA's Energy Systems Program).

Some questions MESSAGE should help to answer:

- What is the optimal timing for the implementation of new energy supply technologies?
- What is the future potential of clean energy, such as electrolysis, liquefaction and gasification of coal and large-scale solar technologies?
- To what extent can soft options such as wind power and local applications of solar power help?
- What constraints does the environment impose on the "optimal" energy strategy?
- What are the direct capital requirements of different energy supply strategies?
- What is the appropriate role of nuclear energy in the future supply of energy?
- What are the ranges of possible mixes of the long-term energy/delivery options?
- To what extent will or could changing end-use patterns improve the overall efficiency of the energy system?

- What does a decrease in import dependency cost?

Questions that lie outside the scope of MESSAGE:

- What are the impacts of different energy supply strategies on the economy?
- Is a zero growth of energy demand desirable?
- Are small-scale soft technologies really beautiful?
- What will the development of world oil prices be?
- To what extent will the expected price rises of delivered energy change life-styles?

2 DESCRIPTION OF THE MODEL

MESSAGE is a dynamic linear programme for comparing alternative existing and new energy supply technologies for the primary and secondary conversion, distribution and end-use of energy in order to satisfy each of the different components of a given useful energy demand. A graphical representation of the components of the energy system being modelled and its boundaries is shown in Figure 2. The model encompasses the following areas of the energy system:

- primary energy resource consumption and transport;
- central station conversion;
- secondary energy transport and distribution;
- decentralised conversion and final use of energy; and
- discharges of residuals to and consequential impact on the environment by each of the above activities.

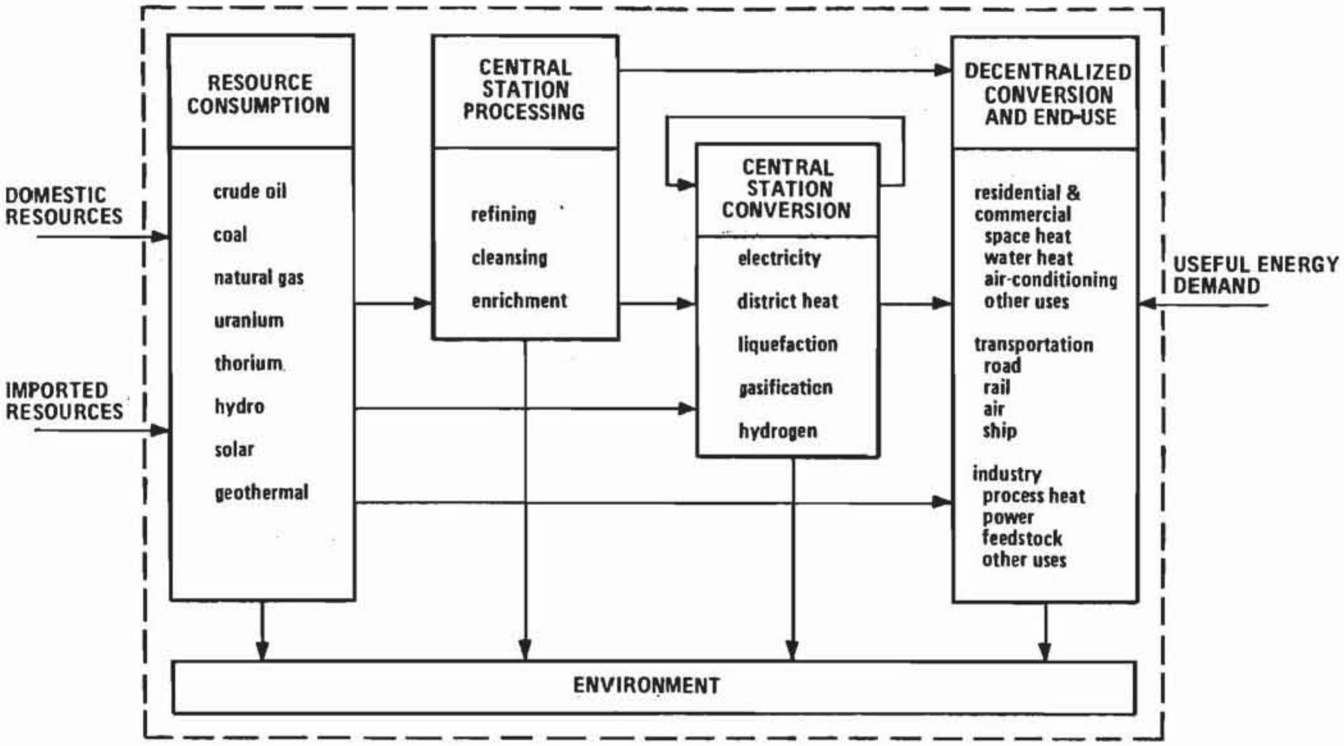

Figure 2 The components of the energy supply system modelled by MESSAGE

Constraints are imposed by the availabilty of primary resources and various technological and normative requirements. These constraints can be summarised under the following headings:

- energy supply and demand;
- primary energy resources;
- conversion technology capacities;

- technological introduction rates;
- environmental impacts; and
- capital availability.

The main objective of the model is to form a consistent and comprehensive framework for analysing all of the major alternative energy supply options open to a region in satisfying future energy demand. Especially the medium- to long-term aspects of the energy supply problem are placed in the foreground of the analysis. The model is not designed to carry out detailed appraisal of minor modifications of or improvements to existing technologies, nor are we concerned, for instance, with relative changes in demand for the numerous grades of liquid fuel - except where this could have major environmental consequences.

2.1 Model development

For obvious reasons it is not desirable to take the most elaborate version of a model for test and trial runs. Also we feel that for gaining experience on how the model reacts it is useful to implement it in stages. The development of MESSAGE, therefore, has been divided into two major stages. The first stage, MESSAGE I, traces the flow and conversion of the various forms of primary energy resources through the central station conversion processes into forms of secondary energy more suitable for final consumption. Thus the (exogenous) energy demand sectors of MESSAGE I for secondary energy are:

- electricity;
- district heat;
- hydrogen;
- coal;
- liquid fuels;
- gaseous fuels.

An inventory is also made of the pollutants discharged by the central station conversion processes.

MESSAGE II takes the flow of secondary energy through the next stage of the energy supply system, namely the transportation, distribution, decentralised conversion and final use of energy in satisfying "useful energy demand" [4]. The exogenous demand sectors of MESSAGE II are segregated into residential and commercial, industrial and transport sectors as shown in Table 1. The useful energy demand of the residential and commercial sectors is used directly, whereas the industrial and transport sectors are first reaggregated to nonsubstitutional final energy demand. An inventory is made of the discharge of pollutants from the decentralised conversion technologies and additionally, there is a more detailed analysis of the environmental impacts of the entire energy supply system.

Table 1 The energy demand sectors

residential and commercial	industrial	transport
- space heating	- power	- road
- water heating	- process heat	- rail
- air conditioning	- feed stock	- air
- other uses		- sea

The first stage, MESSAGE I, is a consistent model in its own right whereas MESSAGE II is only an extension of the first stage. Together MESSAGE I and II form <u>one</u> coherent model - namely the model described in this paper. The first stage, MESSAGE I, has already been completed and applied to the analysis of actual case studies whereas the second stage, MESSAGE II, is not not yet fully operational. As we have pointed out above, stage I emphasises the central station conversion of primary energy resources whereas

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[4] The term "useful energy demand" thus refers to the amount of energy required to provide a level of service to the final user, e.g. in maintaining a warm room or to vacuum-clean a floor. The useful energy demand is a direct measure of a society's need for energy. (This depends in turn on insulation standards, climate, life-styles, prosperity, etc). This and other working definitions used in this paper are contained in the Appendix.

stage II concentrates on decentralised end-use technologies but the distinction between the two stages is nevertheless an arbitrary one. Message II is not treated as a seperate piece of research work. Rather, as sections of the development work are completed, they are included in the operational model, which thus continuously grows in size. For this reason, it is difficult to indicate always in the paper that part of the description which refers to MESSAGE I and that which refers to MESSAGE II. The size of MESSAGE I at the present time varies (with minor modifications) in the neighborhood of 1000 constraints and 2000 variables when it is set up with a time step of 5 years and a 50 year planning horizon. Dependent on the level of aggregation, the extension MESSAGE II would imply at least a doubling in the size of the linear programme.

2.2 Outline of the presentation

For descriptive purposes MESSAGE can be subdivided into three major sections or modules:[5]

- central station fuel and energy conversion technologies;
- transportation, distribution and final consumption of energy;
- environmental impacts.

Before turning to a detailed description of these three modules, we introduce a simplified mathematical formulation of the linear programme that will help to illustrate the general structure of the model without at once including too much confusing detail.

A number of important points, such as the nuclear fuel cycle and the load demand regions for electricity and space heating demand, will not be touched on in the simplified

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[5] In calling each of these three sections a module we do not mean to imply any sense of independence between them. The modules are completely interdependent and together form one linear programme. The arbitrary division of MESSAGE I and II does not exactly correspond to the above division but MESSAGE I does contain the whole of the central station conversion module.

description. These and other topics including a detailed consideration of the possibilities for district heating, transportation and distribution of energy and environmental impacts will be discussed separately in the following sections.

First, we will deal with the module of the central conversion technologies, desribing the nuclear fuel cycle and explaining why it is necessary to model the seasonal fluctuations of demand for electricity, air conditioning and space heat (thereby introducing the possibilty of off-peak production, for instance, of hydrogen as a substitute for fossil-based fuels). It is also shown how the central conversion module can be extended to model the operation of to hybrid plants producing variable proportions of joint products (i.e. electricity and district heat).

After this we discuss in more detail the module covering the transportation, distribution and end-use of secondary energy. It will be shown that it is necessary to disaggregate the useful energy demand according to the population (and thus implicitly the energy demand) density. This is required not only for considertion of the varying costs of transporting and distributing energy but also in assessing the impact of energy supply systems on the environment.

The presentation of the environmental impact module then concludes the mathematical description of the structure of MESSAGE.

2.3 General model structure

The regional or national energy system can be conceptualised as a network of operations and processes transforming various primary energy sources into a form of energy more suitable for final use. Each process or operation can be viewed as a "black box" defined by its flows of inputs and outputs, both of mass and energy, and of economic and ecological factors; the characterisation of a technology is completed by its unit capital cost, construction time and economic lifetime. This is shown schematically in Figure 3 for the case of the gasification of coal using nuclear process heat from a high temperature reactor.

A conversion process is linked to the overall system by its flows of energy inputs and outputs. Each primary energy resource is either converted into a secondary energy form by a central station conversion process (e.g. coal converted to electricity) or used directly as a fuel by a decentralised

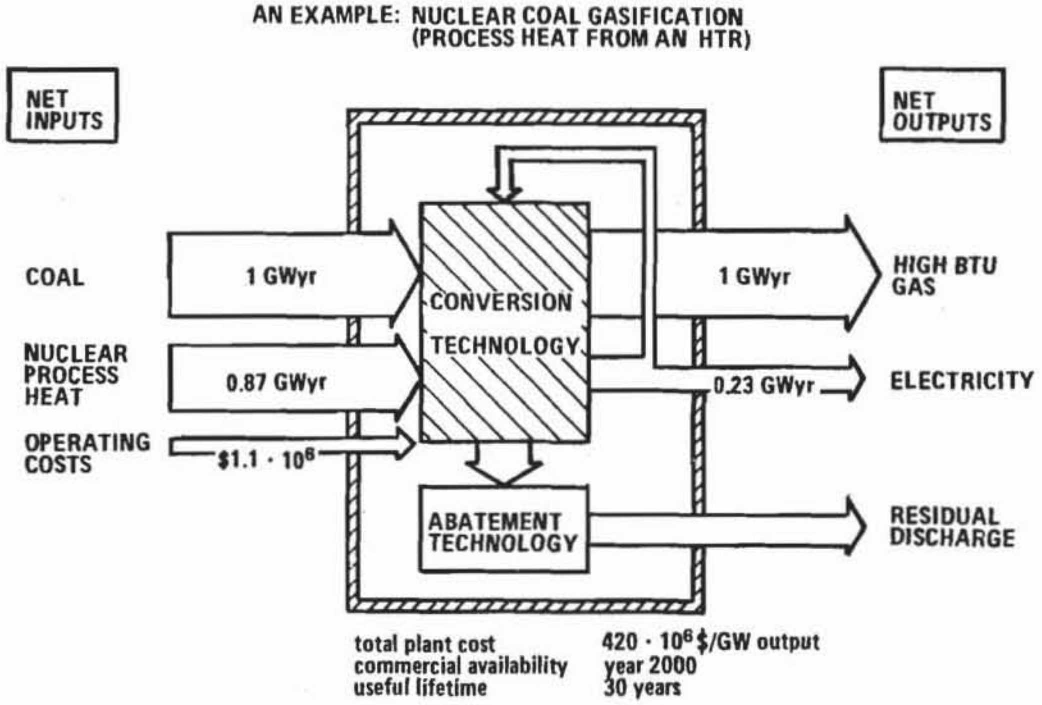

Figure 3 A conceptualised view of an energy conversion technology

conversion or end-use technology (e.g. coal used in open fires for space heating). Both secondary energy and that proportion of primary energy not converted in central stations must then be transported, distributed and converted once more by end-use devices in order to satisfy the useful energy demand in the residential and commercial, the transportation and the industrial sectors.

Before we can start with the formal mathematical description it is necessary to introduce some general points on our notation:

- In order to formulate the dynamic equations of the model the time up to the planning horizon is divided into n_t time intervals $(1, 2, ., t, .., n_t)$ each of length δ_t. The current time interval of any variable will be denoted by (t) following the variable (i.e. $x(t)$). When all the variables in one constraint fall in the same time period the "t" will be omitted if no confusion could arise.

- In general, we try to follow the usual convention that upper case Roman letters denote matrices and lower case Roman letters vectors. Scalars are generally denoted by Greek letters except for subscripts or superscripts. i and j are used to index rows and columns, respectively, and m and n give the row and column dimensions.
- Apart from the notation set out below, we do not necessarily give any unique meaning to other letters denoting coefficients or variables but explain the meaning of the notation used to describe each relation as it occurs in the text.

The most important activities of the model are then defined as follows:

$x(t)$ is an $\{n\}$ vector representing the level of production measured in output units of the supply technologies (the "black boxes" described above) in period (t);

$y(t)$ is an $\{n\}$ vector representing the additional capacity of $x(t)$ created in period (t);

$x(t)$ and $y(t)$ can be partitioned to correspond to central fuel and energy conversion and end-use processes, i.e

$$x(t) = x_p(t) : x_s(t) : x_u(t)$$

the subvectors being of length n_p, n_s and n_u respectively;[6]

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[6] In the detailed description later in the paper, we will abandon this distinction between x_p and x_s since MESSAGE does not treat these activities differently. On the other hand, x_u is further partitioned corresponding to the population/energy density classes mentioned above and handled somewhat differently than in the present simplified description. To avoid the use of too many subscripts and superscripts we denote x_u by u when discussing end-use and environmental impacts.

$r(t)$ is an $\{m_r * n_r\}$ vector of primary energy resources, where m_r is the number of different resources or forms of primary energy and n_r is the number of resource categories (assumed equal for each primary energy source to simplify the exposition) available. ($r(t)$ can also be regarded as an $\{m_r x n_r\}$ matrix $R(t)$);

$z(t)$ is an $\{m_u\}$ vector of useful energy demand;

m_r refers to the number of types of primary resources;

m_p and m_s refer to the number of different forms of energy produced by the central station conversion of primary resources and the further conversion of secondary energy forms;

m_u refers to the energy forms produced by end-use devices, i.e. the number of useful energy demand categories.

The objective function

The objective function can be stated as the minimisation of primary fuel costs plus operating and maintenance costs (excluding fuel) for energy conversion technologies plus the cost of adding additional production and conversion capacity, each element discounted over time.

$$\sum_{t=1}^{n_t} \beta(t) \; (b_r^{'} r(t) + c_p^{'} x_p(t) + c_s^{'} x_s(t) + c_u^{'} x_u(t) + d_p^{'} y_p(t) + d_s^{'} y_s(t) + d_u^{'} y_u(t)) \qquad (1)$$

where

$\beta(t)$ denotes the discount factor;

b, c and d are unit cost vectors of primary energy sources, operating and maintenance and capital costs, respectively; and the subscripts

p, s and u refer to (primary) fuel processing, (secondary) energy conversion and end-use, respectively.

Supply and demand constraints

The general form of the supply and demand constraints of the energy conversion technologies can be illustrated in the following way:

$$\begin{vmatrix} -V_{ru} & -V_{rs} & -V_{rp} & A_r \\ -V_{pu} & -V_{ps} & A_p & \\ -V_{su} & A_s & & \\ A_u & & & \end{vmatrix} \cdot \begin{vmatrix} x_u \\ x_s \\ x_p \\ r \end{vmatrix} \geq \begin{vmatrix} 0 \\ 0 \\ 0 \\ z \end{vmatrix} \qquad (2)$$

This means that, in general, there is a hierarchical pattern in the supply relationships, i.e. "lower" activities satisfy the demands of "higher" activities, the "highest" being those activities that satisfy the final demand vector z. Since the variables are measured in units of output, the A-submatrices consist of ones and zeroes, whereas the V-submatrices contain the conversion ratios of the technologies (i.e. the reciprocals of the efficiencies) and zeroes. Thus V_{rp} is an m_r x m_p is a matrix giving the primary energy resource input requirements of the central fuel conversion processes in the production of one unit of the main output of the processes.

Resource constraints

The cumulative use of a primary energy resource category must be less than the total available supply, thus

$$\delta_t \sum_{t=1}^{n_t} r_{ij}(t) \leq s_{ij}(n_t) \qquad \left| \begin{array}{l} i \leq m_r \\ j \leq n_{r_i} \end{array} \right. \qquad (3)$$

where

m_r is the number of resource types; and

n_{r_i} is the number of categories of resource i.

In MESSAGE I, or in other words for the present operational model, it has been assumed that the total availability of resources, the right hand side of equation 3, is constant over time.

Capacity constraints

The capacity of each process is given by the sum of the additions to capacity in the present and previous periods lying within a time interval less than or equal to the working life of the facility. The actual output of that process must then be less than or equal to the capacity times the load factor.

Additionally, it must hold that the total capacity for supplying each demand category be greater than or equal to the projected demand plus some reserve capacity.

Technological introduction rates

It is necessary to constrain the rate at which a new (and untried) technology can be implemented. This is not only necessary with respect to the rate at which industry can tool up to the direct and indirect requirements of the large-scale production of the new technology, but also to avoid large-scale failure of energy supply caused by possible temporary withdrawal of the technology due to unforeseen development or operational problems. This is achieved by the constraint

$$y(t) \leq \gamma \, y(t-1) + g \qquad (4)$$

where

g is a constant vector allowing for an initial start-up capacity;

γ is a constant (determined empirically) reflecting the maximal introduction rate of a new technology.

Environmental constraints

Different pollutants emitted by energy conversion processes have various kinds of impact on the environment. Some pollutants (which decay quickly) on affect only the local environment (SO_2, particulates) and others (long-lived radio nuclear pollutants, CO_2) have a global impact. The ambient concentrations of those emissions whose impact is at the local level are calculated by a simple dispersion model; these concentrations are then related to populations by use of a simple model of urban population distribution. The impact of emissions whose effect is global is estimated by the application of dilution factors. Suppose the local impacts are given by the vector $q_l(t)$ and the global impacts by $q_g(t)$, then these can either be constrained below some standard level

$$q_l(t) \leq \text{standard}_l \qquad q_g(t) \leq \text{standard}_g \tag{5}$$

or optimised by their inclusion in the objective function:

Minimise

$$\sum_{t=1}^{n_t} \beta(t) \ (\text{energy supply costs} + w_l' q_l(t) + w_g' q_g(t)) \tag{6}$$

where w is a vector of weights of the environmental impacts of the pollutants.

The abatement technologies are dealt with by expanding the vector of technological processes x to include controlled technologies (i.e. the normal conversion technology plus the abatement technology). Either constraining or minimising the level of impacts could then force the pollution-abated, and more expensive, technology into the solution.

Capital availability

Additional constraints are required to ensure that the rate of capital investment in the energy sector does not exhibit periodic peaks related to the average life-cycle of a dominant technology. These constraints are of the following form:

$$\sum_j (y_j(t+3) + y_j(t+2)) \geq \alpha \left[\sum_j (y_j(t+1) + y_j(t)) \right] \tag{7}$$

where α is a constant which would allow for a slow decline in overall investment once an equilibrium state is approached at which time only replacement investment would be necessary.

2.4 Central station fuel and energy conversion module

The structure of the central station conversion technology module is outlined in Figure 4, which illustrates the flow of different forms of primary energy resources through the various conversion processes into forms of energy more suitable for final consumption. The centralised technologies include both fuel and energy conversion technologies.

Primary energy resources

The present version of the model includes the following primary energy resources:

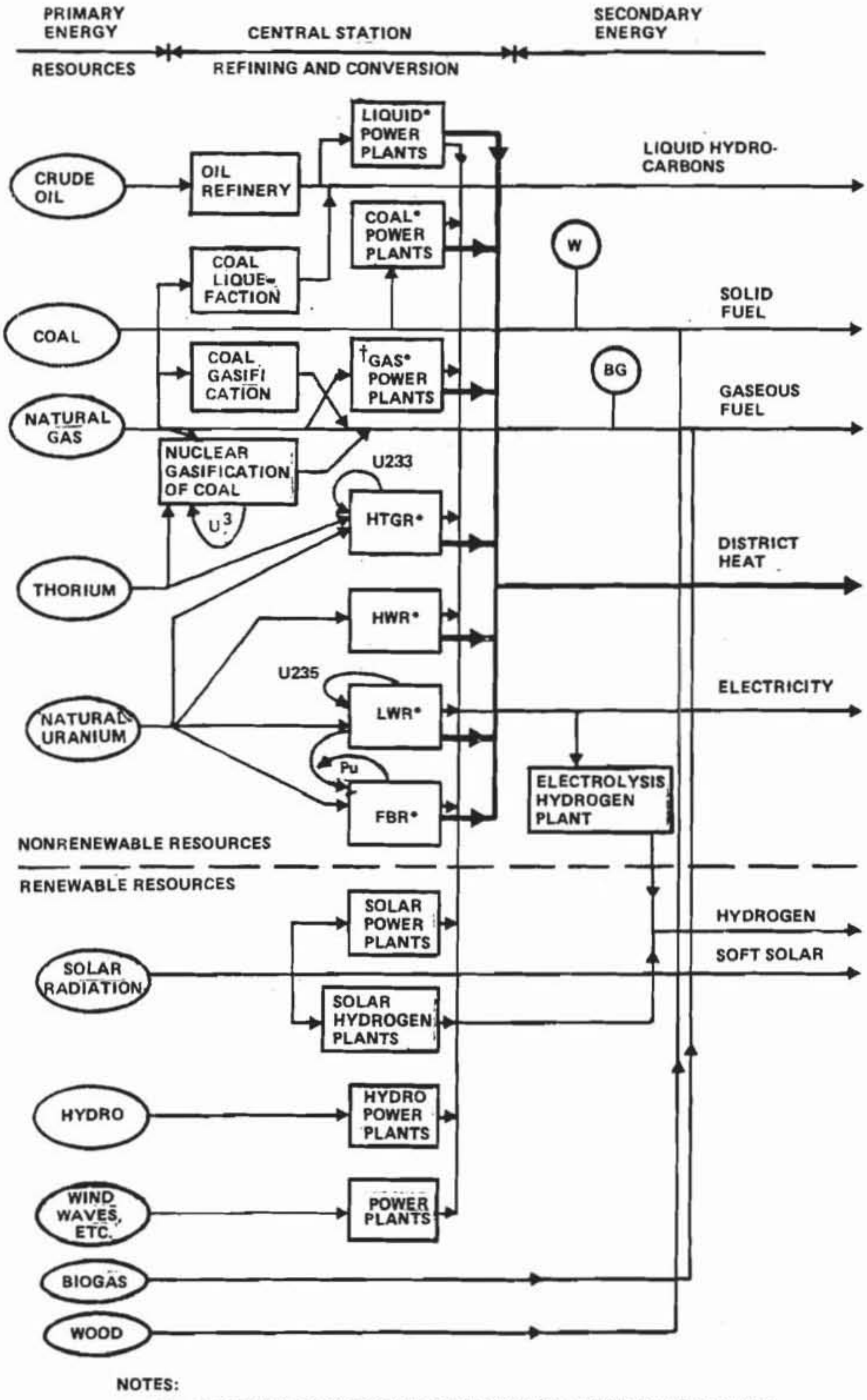
- crude oil;
- coal;
- natural gas;
- uranium and thorium;
- direct use of solar radiation; and
- hydro;

but it can easilly be extended to include other kinds of resources, especially the indirect use of solar energy, such as geothermal, waves, biomass or wind.

Indigenous resource categories

The cost of extracting primary energy resources and of making them available to the centralised conversion technologies depends on the location, quality and extent of the deposits and the difficulty of extracting them. At any particular point in time and cost level, there is an upper limit to the amount of a primary resource of a particular quality and location which can be extracted. As time moves on, deposits with low cost characteristics become depleted and more expensive deposits must be explored. But new discoveries of deposits also occur over time, increasing the availability of resources at all levels of cost and quality.

The dynamic non-linear relationship between the cost of extraction and the quantity of the resource available in each time period is approximated in the model by a stepwise



NOTES:

*EACH OF THESE BOXES COULD REPRESENT (1) A DISTRICT HEAT PLANT, (2) AN ELECTRICITY GENERATING PLANT, OR (3) A COMBINED PLANT.

†THIS BOX INCLUDES GAS–STEAM AND GAS TURBINE PLANTS

Figure 4 Structure of the central station conversion technology module linearisation. An optional number of resource categories is defined for each primary energy resource, each category being defined by its cost of extraction, quality and location.

Suppose that $s_{ij}(t)$ represents the total availability of resource i of category j at time t^7. Then we can write the constraints on the cumulative consumption of indigenous resources as follows:

$$\delta_t \sum_{t=1}^{t} r_{ij}(t) \le s_{ij}(t) \qquad \left| \begin{array}{l} i \in m_r \\ j \in n_{r_i} \\ t \in n_t \end{array} \right. \tag{8}$$

where

$r_{ij}(t)$ is the annual consumption of indigenous primary energy resource i of the resource category j;

δ_t is the length of the time period in years;

m_r, n_{r_i} and n_t are the number of primary resource types, the number of resource categories of resource i and the number of time periods respectively.

When $t = n_t$, the last equation in this set is

$$\delta_t \sum_{t=1}^{n_t} r_{ij}(t) \ge s_{ij}(n_t) \qquad \left| \begin{array}{l} i \in m_r \\ j \in n_{r_i} \end{array} \right. \tag{9}$$

In the present version of MESSAGE I, only this last equation is included but, when refinements to the resource model are complete, it will be possible to include the complete set of equations given above. Since it is reasonable to expect that some new resources, at the very least, will be discovered, the value of $s_{ij}(n_t)$ used for MESSAGE I includes conservative estimates of new discoveries that are likely to be made up to the planning horizon. This implies, of course, an over-estimate of the resources available in the earlier planning periods.

Including several resource categories in the model not only allows us to take account of different primary energy

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[7] By definition $s_{ij}(t)-s_{ij}(t-1)$ is the total amount of the resource discovered in the period (t-1) to t.

extraction costs but also permits a distinction to be made between different fuel qualities (e.g. SO_2 content) and the geographic location of resource deposits. The latter distinction is necessary in allowing for the costs of transporting primary energy resources to the central station conversion plants (usually sited near to large urban centres).[8]

Import of primary resources

The constraints given above refer only to indigenous resources. Many countries, however, depend heavily on imported primary resources. The Federal Republic of Germany, France and Japan are especially dependent (importing over 70% of their fuel requirements) but many developing countries are in a similar predicament. It is therefore necessary to introduce additional resource categories for imported resources. In practice, only one import category for each fuel i is defined for the model but with a "cost" (or more accurately, with respect to imports, a "price") which increases over time (this assumption is a pragmatic one but there are no technical reasons, related to the specification of the linear programme, why it could not be relaxed.)

Let us suppose that

$r_{ik}(t)$ represent the annual rate of consumption of resource i imported in time t (i.e. an $(n_{r_i}+1)^{th}$ category is defined); and

$k_i(t)$ be the maximum "availability" of an imported crude fuel i in each year;

then

$$r_{ik}(t) \leq k_i(t) \tag{10}$$

As a first round, $k_i(t)$ is estimated by a scenario approach but this first estimate will be revised by the iterative interactions of the complete set of models until a balance of world trade in energy resources is achieved.

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[8] A cautionary word should be added here: The emphasis of MESSAGE is on the options which are available in the conversion, distribution and end-use of energy rather than on the availability of natural resources. Increasing the number of resource categories beyond 5 or 6 would imply a depth of detail on the resource side which MESSAGE was not designed to handle.

An often stated policy goal of energy planners is to reduce or limit the dependency of a region on imported energy. It is important to be aware of the consequences of following such goals. By including constraints on the level of imported energy, an estimate of the "cost" of achieving these goals is given by the corresponding shadow prices. Total imported energy can then be limited to an arbitrarily fixed proportion α (α might well be greater than 1) of the total consumption of indigenous resources plus a correction to adjust for the use of solar and other renewable energy sources. Thus

$$\sum_i r_{ik}(t) \le \alpha \left[\sum\sum_{ij} r_{ij}(t) + \left| \begin{array}{c} \text{primary equiv.} \\ \text{of actual} \\ \text{solar energy} \\ \text{used} \end{array} \right| \right] \tag{11}$$

The resources available for export are treated as an additional exogenous demand category - a balance between imports and exports being achieved at the world level by iterative runs of the complete set of regional models.

The total annual consumption of each primary energy resource is the sum over each resource category plus imported resources. Using an asterix to denote the sum over an index we can write

$$r_{i*}(t) = \sum_{j=1}^{n_r} r_{ij}(t) + r_{ik}(t) \tag{12}$$

Thus r_{i*} represents the total annual consumption of the primary energy resource i which is equal to the amount of i used in the centralised fuel and energy conversion processes plus that amount used by the end-use technologies. The general form of this constraint (except for the consumption of national uranium and thorium) is given by

$$r_{i*}(t) = \sum_{j=1}^{n_x} v_{ij} x_j(t) + \sum_{k=1}^{n_u} v_{ik} u_k(t) \tag{13}$$

where

x_j is the annual production of the j^{th} central station conversion process;

u_k the annual production of the k^{th} end-use technology;

v_{ij} and v_{ik} are the specific inputs of primary energy resource i required to produce one unit of output of the process j and k; and

n_x and n_u are the total number of centralised conversion processes and end-use technologies.

Note: the coefficients v_{ij} and v_{ik} will often be zero.

In the case of nuclear facilities, not only must the annual fuel requirements be met but an initial start-up inventory and the lag times involved in the nuclear fuel cycle must be considered. Since the modified nuclear consumption balance equations are similar to the equations describing the consumption of man-made fuels - such as plutonium - we leave their specification to the later section describing the nuclear fuel cycle.

Fuel conversion and processing

The extraction of crude oil, natural gas and coal provides fossil energy which is either used directly (i.e. in the case of coal for space heating) or converted into another form of fuel or energy. A number of technologies for refining crude oil, coal gasification and coal liquefaction are defined in the model. Since a large number of techniques are available for each of these processes it is necessary to be selective. Generally the dominant (or, in the case of new technologies, the most promising) technique is chosen[9]. Especially in the case of coal, it is necessary to take account of abatement techniques for cleaning the emissions, so that in addition to the conventional technology we include a "clean" or controlled technology representing the most promising abatement method.

Coal liquefaction and gasification

The importance of introducing technologies to produce synthetics from coal is to use the abundant coal reserves by first converting them to a more convenient and environmentally acceptable form. In this way, coal can supplement (and eventually replace) natural gas and oil if, or when, these reserves run out. Numerous processes have been investigated to produce a synthetic gas to substitute for natural gas. We can distinguish between two types of processes, namely conventional and nuclear. In the conventional processes part of the total coal input is used to provide process heat, whereas in the nuclear processes

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[9] Two or more alternative techniques could, of course, be included in the model: The structure of the alternative technique would be unchanged whereas the cost, efficiency and emission coefficients would be different.

the process heat is provided by the reactor. The nuclear process is therefore more efficient in terms of coal input to gas output resulting in an overall saving in coal and - in countries with high coal costs - in lower production costs. Similar arguments hold for the liquefaction of coal using nuclear process heat.

The electricity and district heat production system

In contrast to most other commodities, electric energy and district heat cannot be stored economically in large amounts at the present time; they have to be consumed simultaneously with their production. Due to this fact, the load characteristics of the electricity and district heat demand (i.e. yearly and daily fluctuations) have an important impact on the optimal mix of generating equipment. The typical load characteristics of both electrical and district heat demand in the Federal Republic of Germany are shown in Figure 5 [12] which can be summarised as follows:

- The annual variation in demand for district heat is very high but the average annual load duration is low (in the range of 2000 hours per annum depending on climatic conditions).
- The peak demands for district heat and electricity occur at roughly the same time of the year. This must be taken into account when considering a combined district heat/electricity production.
- The daily variation in demand for both space heat and electricity requires additional peak facilities.

Combined production of electricity and district heat

District heat, which uses a central conversion plant to produce space and water heating, has been applied for many years in several countries. Recently, however, the combined production of electricity and district heat has received a lot of attention. When used in combination with a plant generating electricity, steam is discharged at some point in a steam turbine; the steam is then used for space heating. A combined production of electricity and district heat allows significant savings in primary energy. This is due to the fact that using the low temperature steam, with its high condensation energy to produce district heat, only slightly reduces the amount of electricity produced.

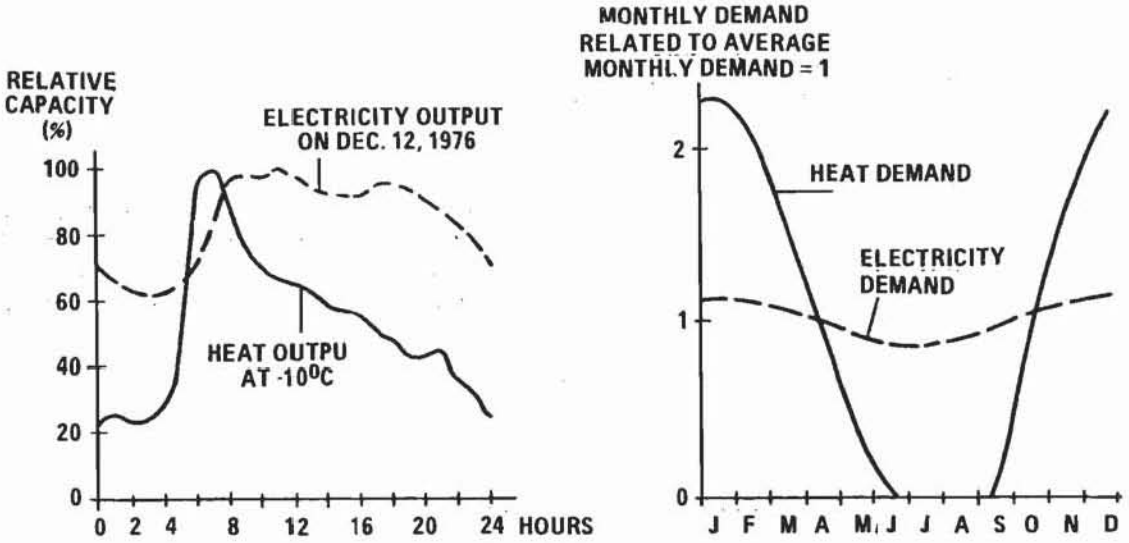

Figure 5 Electricity and district heat load demand curves

Using the otherwise wasted heat of large electricity generating plants for district heat in this way also has environmental benefits. Since the combined plants operate at higher efficiencies, thermal pollution is reduced and air pollutants can be discharged from higher stacks than are usual with smaller district heat plants, greatly reducing the impact of emissions at the ambient level.

Supposing we have a hybrid technology x_j which produces variable proportions of electricity e_j and district heat d_j, then the decrease in electricity output with increasing heat extraction is given by the fraction s_j as follows:

$$s_j = \frac{\text{reduction in electricity output}}{\text{incremental heat output}} = \frac{\Delta e_j}{\Delta d_j} \qquad (14)$$

If we assume that this factor is constant within the variable production scheme of the plant, the relation between electricity and heat production is given by

$$\Delta e_j = e_j^{max} - e_j = s_j d_j \qquad (15)$$

so that if $e_j = e_j^{max}$

then $d_j = d_j^{min} = 0$

The line AB shown in Figure 6 describes the technical possibilities of production: point A corresponds to maximum electric and zero district heat production; point B to maximum district heat and minimum electric production. (For technical reasons there is a lower limit to the share of electricity production in the total power production.)

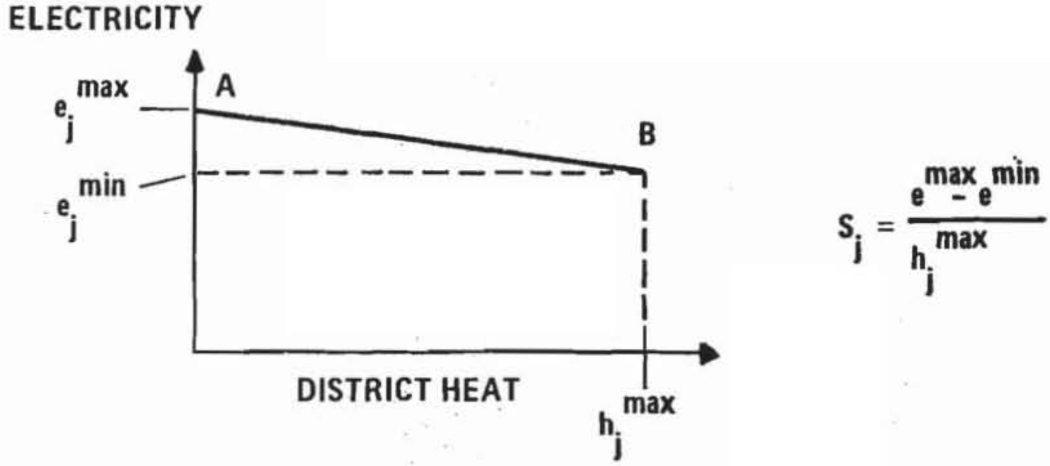

Figure 6 Simplified characterisation of a combined heat/electricity plant

Now let us suppose that the plant x_j has two modes of operation, one at A represented by x_j^e and one at B by x_j^d. Then the energy produced at A and at B is given, respectively, by

$$x_j^e \text{ which equals } e_j^{max} \qquad (16)$$

and

$$x_j^d \text{ which equals } e_j^{min} + d_j^{max} \qquad (17)$$

It is clear that every point on the line AB can now be represented as a linear combination of x_j^e and x_j^d.

The district heat and electricity supply system in MESSAGE

As pointed out above, a (realistic) model for the district heat and electricity supply system must take into account the wide annual variation of demand for both heat and electricity. In the case of a combined generation of heat and electricity, the possible simultaneous occurence of peak demand for electricity and heat must also be considered. In addition, the model should be capable both of representing the variable operating scheme of the combined heat/electricity plants and of finding the optimal mix of different power and heat plants that correspond to their energy generation cost structure (i.e. taking account of the fact that some plants have high capital costs but low operating and fuel costs and vice versa).

In order to understand the approach used, consider that the variation in load can be represented by a standardised load curve. The daily load characteristics can be taken account of by defining a day and night time load curve representing the upper and lower limits of the daily variation of the demand curve. The non-linear demand load curves for electricity (e) and district heat (d) can be represented by a step function, as shown schematically in Figure 7. [10]

If we let

$L_d(t)$ and $L_e(t)$ represent the demand load curves for heat and electricity respectively;

$l \in n_l$ is the set of (time) segments of the step function by which the load curves are approximated; and

---

[10] We simplify again for clarity of exposition. An approximation of the load curves for district heat and electricity production is not in fact carried out (except in MESSAGE I). Rather the exogenous input of the model concerning load characteristics is of useful energy demand (i.e. space heat rather than district heat, lighting rather than electricity). The load characteristics of individual types of plants are an output of the model as will be shown presently when discussing the end-use module.

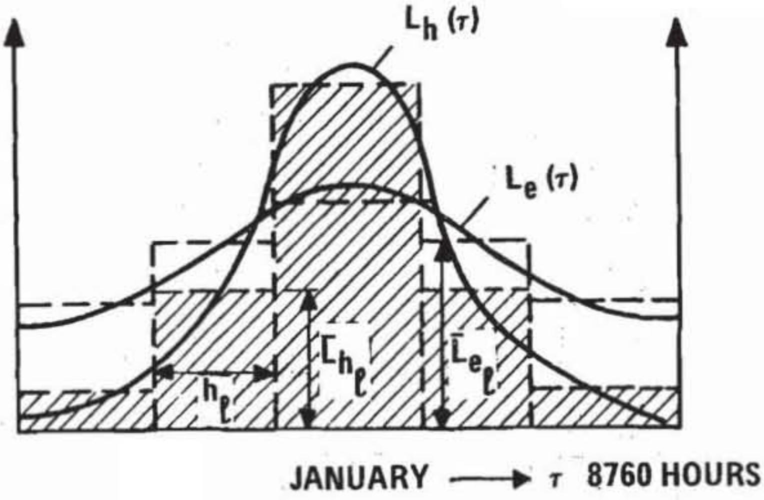

Figure 7   Approximation of load curves

h_l is the length in hours of the lth time segment (load region);[11]

$\bar{L}_{dl}$ and $\bar{L}_{el}$ represent the average load demand in time segment l for district heat and electricity, respectively;

then the following relations hold:

$$(DM_e) = \int_0^1 L_e(t)\,dt = \sum_l (DM_{el}) = \sum_l h_l \bar{L}_{el} \qquad (18)$$

$$(DM_d) = \int_0^1 L_d(t)\,dt = \sum_l (DM_{dl}) = \sum_l h_l \bar{L}_{dl} \qquad (19)$$

where (DM) is equal to the intermediate (endogenous) demand (IM) plus useful energy (exogenous) demand (z).

Within the electricity and district heat supply system we distinguish between three types of plant:

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[11] The quality of the load curve approximation is not only a function of the number of time segments: a small, but carefully chosen, number of time segments of unequal length might give a better approximation than a much larger number of equal length.

- electricity generating plants, $j \in n_e$;
- district heating plants, $j \in n_d$; and
- combined plants, $j \in n_c$, which produce heat and/or electricity in a variable proportion.

The potential variation of the electricity and district heat production capacity within a combined plant is thereby given by

$$c_j = c_j^e + s_j c_j^d \qquad j \in n_c \qquad (20)$$

$$c_j^e \geq a_j c_j \qquad (21)$$

where

c_j^e is the electrical generating capacity;

c_j^d is the district heat capacity; and

a_j is the minimum share of electricity to total production (measured in electricity equivalent units).

Demand constraints

The generation of electricity and heat must be equal to or greater than the exogenous useful energy demand plus the intermediate demand in each time segment (load region) of the annual period. Thus for

a) electricity demand

$$\sum_{j \in n_e} x_{jl} + \sum_{j \in n_c} x_{jl}^e \geq z_{el} + (IM_e) \qquad l \in n_l \qquad (22)$$

b) district heat demand

$$\sum_{j \in n_d} x_{jl} + \sum_{j \in n_c} x_{jl}^d \geq (DM_{dl}) \qquad l \in n_l \qquad (23)$$

where

(IM_{el}) is the intermediate demand for electricity;

(DM_{dl}) is the (endogenous) demand for district heat; and

$l \in n_l$ is the set of load regions.

Production capacity constraints

Individual plant constraints: The energy supplied from each plant in any load region l must be smaller than the potential production limited by the available capacity. Thus for

a) power plants

$$\frac{x_{jl}}{h_l} \le c_j \qquad j \in n_e \qquad (24)$$

b) district heating plants

$$\frac{x_{jl}}{h_l} \le c_j \qquad j \in n_d \qquad (25)$$

c) combined plants

$$\frac{x^e_{jl} + s_j x^d_{jl}}{h_l} \le c_j \qquad (26)$$

$$x^e_{jl} \ge a_j (x^e_{jl} + s_j x^d_{jl}) \qquad j \in n_c \qquad (27)$$

where

a_j is the minimum share of electricity in the total production of electricity and district heat of facility j; and

s_j is the reduction of electricity output for unit increase of heat output of j.

Electricity and heat production constraints: The electricity and heat production capacity actually available must exceed the highest load demand in all load regions plus some reserve capacity for unplanned shutdowns and/or unexpected peaks in demand.

a) electricity

$$(z_{el} + (IM_{el}))(1 + r_e) \le (\sum_{j \in n_e} c_j + \sum_{j \in n_c} c_j) h_l \qquad (28)$$

b) district heat

$$z_{dl} (1 + r_d) \leq \left(\sum_{j \in n_d} c_j + \sum_{j \in n_c} c_j \frac{1}{s_j} \right) h_l \qquad (29)$$

The electricity and district heat supply technologies considered in the present version of the model are listed in Table 2. The electricity produced by hydroelectric power plants is treated as an exogenous input due to the different individual cost figures of each plant.

Table 2 Electricity and district heat plants

supply technology	electricity	district heat	electricity & heat
coal fired plant	x	x	x
gas fired plant	x	x	x
light water reactor	x		x
fast breeder reactor	x		
high temperature reactor	x		x
solar power plant	x		
hydro-electric power plant	x		

Hydrogen production

Although electricity can be produced from a wide variety of energy sources and is extremely clean in the end-use, it is questionable if an all-electric economy is feasible or even desirable. Since in the long run we shall run out of fossil fuels - at least of oil and natural gas - it will be wise to consider, in addition to electricity, an alternative synthetic fuel that could be used in much the same way as our present fossil fuels (e.g. in powering motor vehicles). Hydrogen is one such fuel and could possibly become a valuable alternative to electric energy, having certain advantages in storability and transportability. The special appeal of the electrolytic production of hydrogen is that it can "store" electric energy and thus make use of excess electricity generating capacity at off-peak times.

The production of hydrogen is presently carried out by the steam reformation or partial oxidation of hydrocarbons. With the limited resources of oil and natural gas, these possible sources of hydrogen are not long-term options. Therefore, as long-term alternatives, we consider two production technologies in our model by which hydrogen can be made from non-fossil energy sources such as nuclear or solar energy. One is the electrolysis of water and the other the thermochemical splitting of water. Producing electrolytic hydrogen by electrolytic cells requires electricity, a high-quality energy form, as input. Several electrolytic hydrogen plants have been operated successfully, whereas the thermochemical production of hydrogen is still in a preliminary stage of research and development. The thermochemical process involves the use of a sequential series of chemical reactions producing hydrogen and oxygen, thereby avoiding the requirement of high temperatures in excess of 2000°C for a direct single-step thermal splitting of water.

In the model, we distinguish between the following three hydrogen production processes, namely

- electrolytic hydrogen;
- thermochemical hydrogen using process heat of high-temperature gas-cooled reactors;
- solar hydrogen (thermochemical).

The introduction of additional hydrogen production technologies is easily incorporated in the model.

The nuclear fuel cycle

In the short history of the peaceful use of nuclear energy a great number of reactors concepts have been proposed and developed. Most of them have not, and will not, reach a commercial stage. From the present point of view the most promising seem to be (a) the light-water (LWR) and natural uranium heavy-water (HWR) reactors - both of which are already in commercial use - and (b) the fast breeder (FBR) and high temperature gas-cooled (HTGR) reactors which are not yet commercially available.

The enrichment, fabrication, reprocessing and waste disposal costs are included in the cost coefficients of the objective function of each nuclear power plant type. In the first expression below, we write down the material balance equation of natural uranium and thorium necessary to ensure that stocks of processed natural uranium and thorium are available. This is followed by the material balance equations of the man-made fuels plutonium, uranium 233 and depleted uranium which prevents the stock of these materials from becoming negative. Thus for

a) natural uranium and thorium:

[i $\in$ { natural uranium, thorium }]

$$r_i(t) = \sum_j (v_{x_{ij}} x_j(t+\Delta t_e) - f_{x_{ij}} x_j(t-\Delta t_r)) + v_{y_{ij}} y_j(t+\Delta t_e) - f_{y_{ij}} y_j(t-(l_t+\Delta t_t) \qquad (30)$$

b) plutonium and other man-made fuels:

[i $\in$ { plutonium, uranium-233, depleted uranium }]

$$s_i(t) = s_i(t-1) - \sigma_t \sum_j (v_{x_{ij}} x_j(t+\Delta t_e) - f_{x_{ij}} x_j(t-\Delta t_r) + v_{y_{ij}} y_j(t+\Delta t_e) - f_{y_{ij}} y_j(t-(l_t+\Delta t_t)) \qquad (31)$$

where

$r_i(t)$	is the amount of the natural resource i (either uranium or thorium) used in t;
$s_i(t)$	is the stock of the man-made fuel i at t;
$x_j(t)$	is the annual output of the nuclear conversion process j;
$v_{x_{ij}}$	is the annual replacement requirement of nuclear fuel per unit of annual output;
$f_{x_{ij}}$	is the annual recovery of fuel from reprocessing;
$y_j(t)$	is the additional capacity of the nuclear conversion process j installed in t;
$v_{y_{ij}}$	is the initial inventory requirement of nuclear fuel per unit of capacity;
$f_{y_{ij}}$	is the unit final retirement of fuel on shutdown of the plant;
Δt_e	is the lag time required for preparation and enrichment of new fuels;

Δt_r is the lag time required for reprocessing of spent fuels;

δ_t is the length of the time period in years;

l_t is the lifetime of the facility in years.

2.5 The energy transportion, distribution and end-use module

Energy supply options at the end-use

Options for supplying a region's energy requirements do not only arise from the availabilty of primary energy resources and the state of development of central conversion technologies. Significant options also exist in the consumption of energy at the end-user side in performing a real energy service, either directly satisfying a real human need, or in the production of goods. These end-use technologies have received little attention by energy analysts in the past but, like the central conversion technologies, have wide ranges of efficiencies, environmental impacts and costs. It is therefore imperative to extend the model to include the transportation, distribution and end-use of secondary energy, not only to capture all of the impacts of the energy supply system on the environment, but also to realise the highest possible savings in primary energy resources and capital expenditure by choice of the most efficient or least expensive path through the entire energy supply system, from primary energy resources to the satisfaction of energy needs.

Before explaining the method adopted for taking account of the energy transportation, distribution and end-use technologies, we would like to set out some of the arguments underlying the choice of a comprehensive approach.

Small-scale conversion technologies based on renewable resources

The following small-scale decentralised conversion or end-use technologies are often included among the new energy options that are expected to make an important contribution in supplying future energy demand:

- solar for room heating and warm water supply;
- biogas production systems; and
- the heat pump.

But the energy which these options might be expected to supply per unit area is limited not only by the natural conditions occurring in the region in question but also by the man-made environment. And, of course, the energy demand per unit area is also a function of the population density. An analysis comparing small-scale decentralised conversion technologies (using renewable resources) with central station conversion ones, must be made in terms of satisfying the same useful energy demand. This analysis must also take at least some account of the regional distribution of population.

Environmental impact at the end-use

The second point relates to the environmental aspect of the energy supply system. A significant amount of the environmental damage caused by the emission of pollutants occurs at the point of the end-use of energy, such as NO_2 emitted by automobiles or SO_2 by coal- and oil-fired space heating systems. This is shown dramatically in Figure 8 The SO_2 emissions of the residential and commercial sector, which make up only 10% of the total SO_2 emissions in the Wisconsin urban area, contribute more than 60% to the ambient dose level.

Efficiencies of end-use technologies

The consumption of energy, or the conversion of high-quality energy into low quality heat, is no end in itself. Energy, along with other resources, is used in our society to produce goods and services, to transport goods and people, to heat and light rooms, etc. The efficiencies involved in the end-use of energy vary widely with regard to the purpose for which the energy is used and the end-use technologies involved. Some figures for the different efficiencies of alternative space heating systems and passenger transportation modes are given in Table 3. This shows that an assessment of the overall efficiency of the entire energy system in satisfying a given useful energy demand must also take into account the different technologies, each with its own particular conversion efficiency, which are available at the end-use.

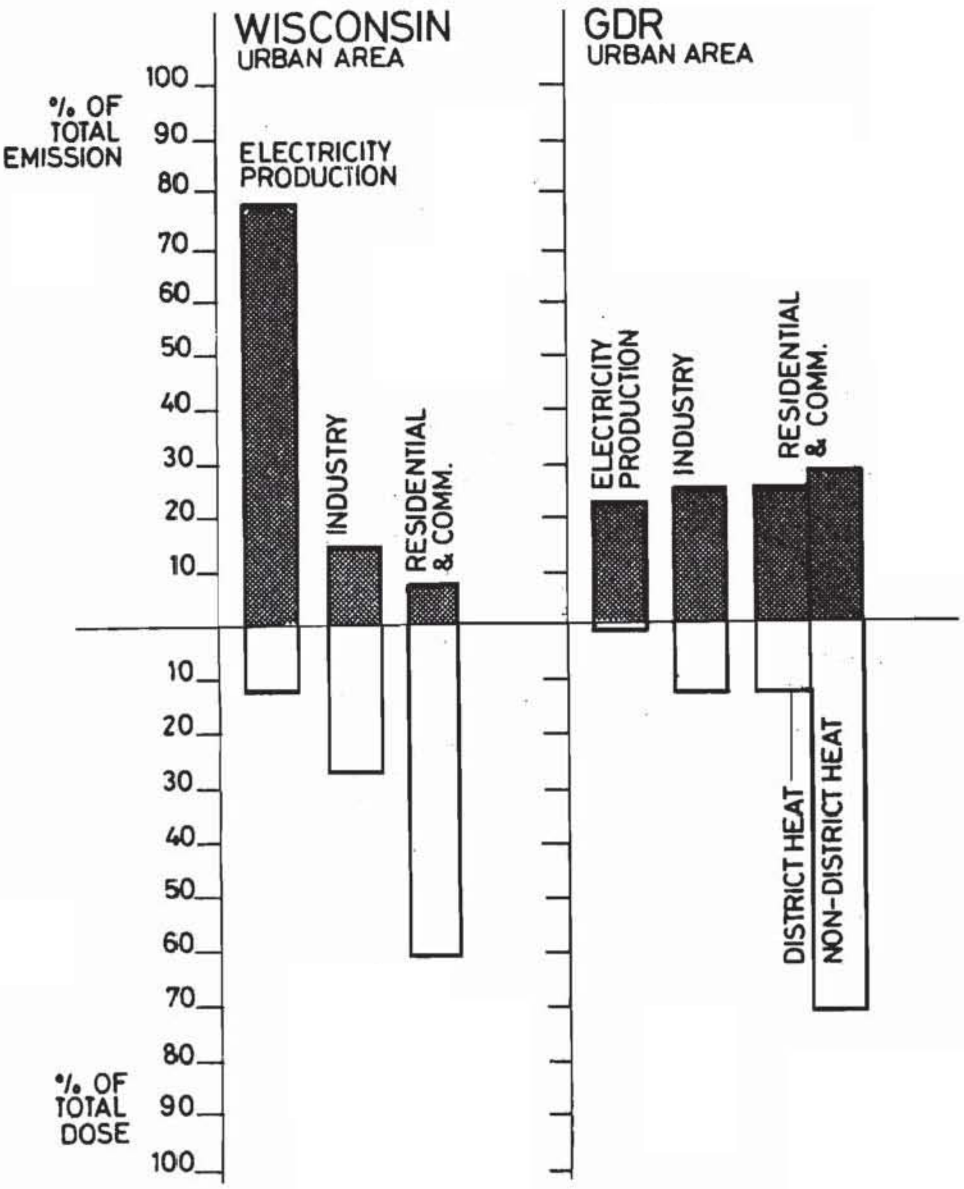

Figure 8 SO_2 emissions and ground-level concentrations, 1970

Capital cost for the transportation and distribution of secondary energy

And last but not least, we would like to draw attention to the capital investments necessary for the transportation and distribution of energy. Table 4 shows the capital investment of the public electricity and district heat

Table 3 Energy efficiency for inter-city passenger traffic and space heating systems

intercity passenger traffic	BTU per passenger mile
buses	1 090
railroads	1 700
private car	4 250
airoplane	9 700

space heating	efficiency (%)
oil oven	46
oil central heating	51
gas oven	61
coal central heating	41
elctrical heating	94

Table 4 Capital investments of the electricity and district heat utilities in 1975

plant type	electricity supply		district heat	
generation	4 640	45.6	67	23.7
transport	4 530	44.6	171	60.4
other	1 000	9.6	45	15.9
total	10 170	100.0	283	100.0

utilities of the Federal Republic of Germany in 1975. In the electricity supply sector, the investments for transport and distribution facilities were nearly as high as for production of electricity and in the case of the district heat supply sectors the investments for transportation and distribution were nearly three times higher than the production facilities.

Energy distribution and load densities

We have already mentioned that some of the decentralised energy options are limited in the amount of energy they can provide per square meter (for example, the average solar energy density in Austria is around 114 W/m^2). In the case of secondary energy produced by central station conversion, it is important to appreciate that their related distribution costs are almost solely a function of the load density (i.e. the amount of energy delivered per unit area: See Figure 9). Especially in the case of district heat, the distribution costs increase dramatically with decreasing load density. It is clear from these figures that the load density is an important factor in modelling the energy transport, distribution and end-use part of the overall energy supply system.

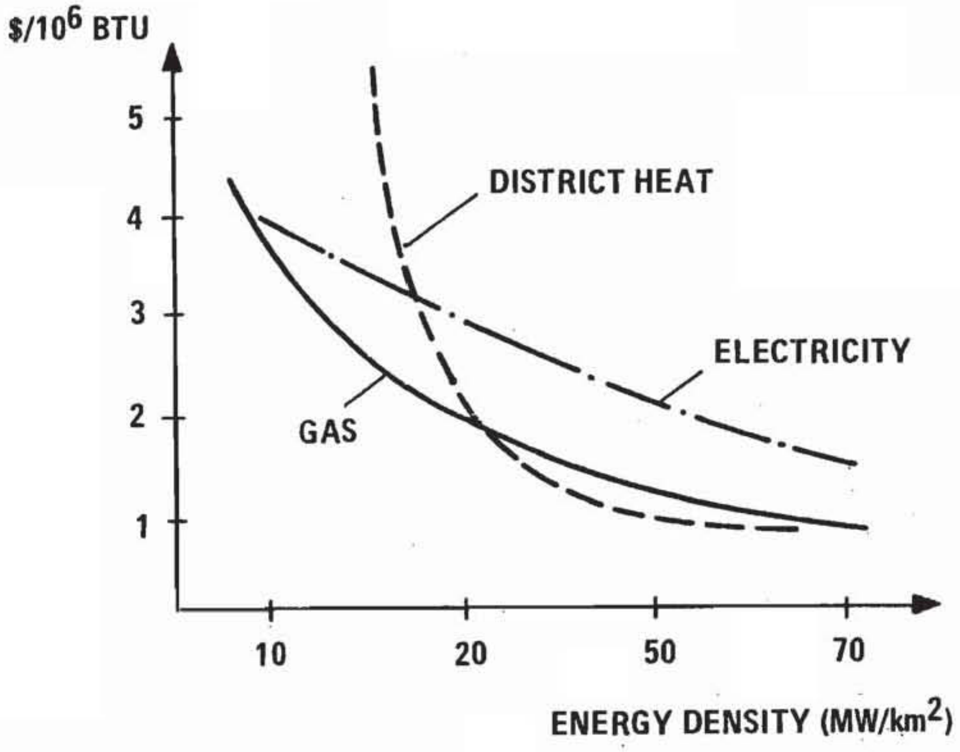

Figure 9 Energy distribution costs with respect to energy density, FRG, 1975

As one might expect, the load density - or the energy consumption density - is directly related to the population density, at least in the case of the residential sector. These relationships are shown in qualitative in Figure 10. The left part of the figure refers to the energy consumption density and the right part to the population density over the area of the Federal Republic of Germany. The actual values are 1970 figures. The solid lines of different

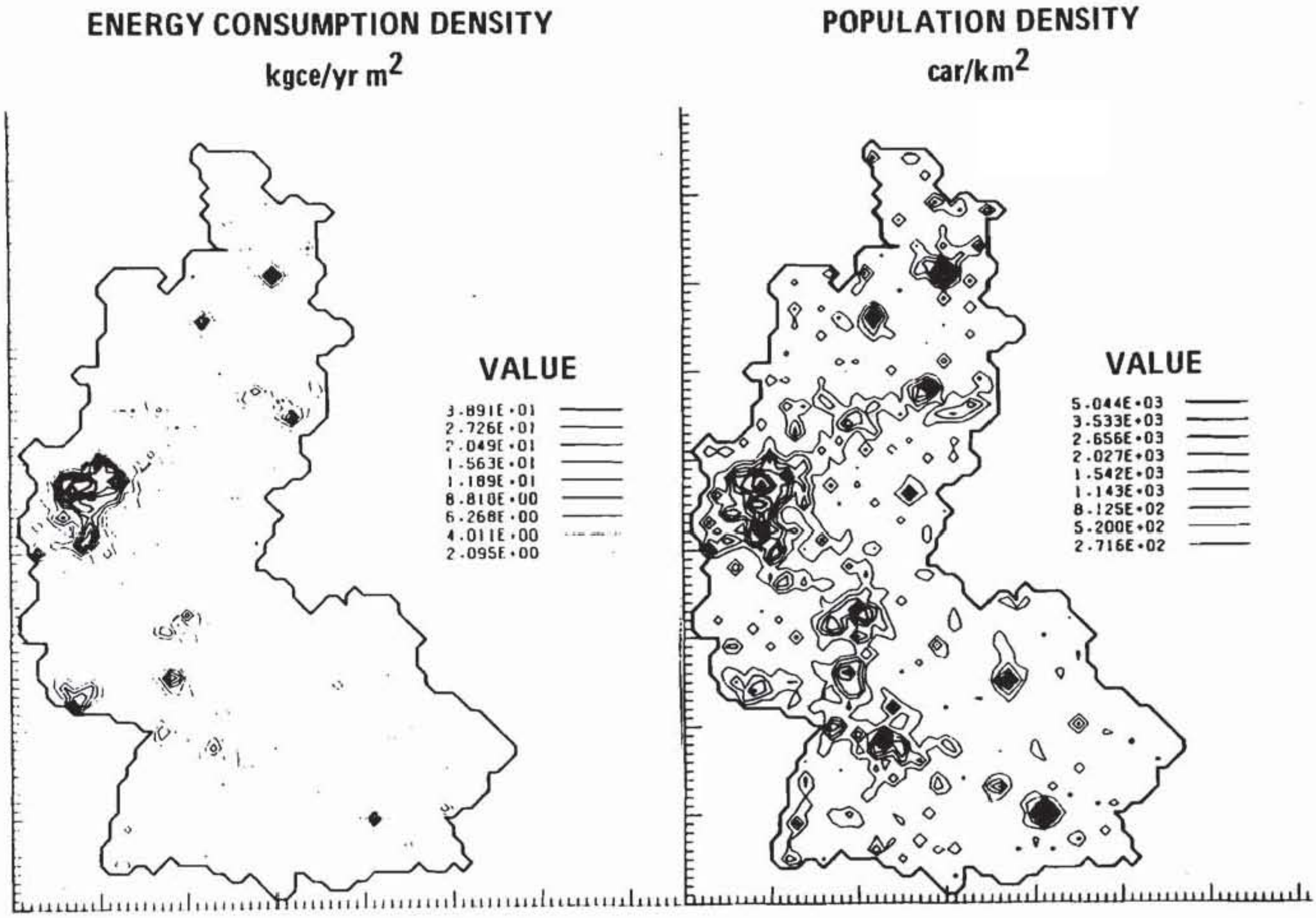

Figure 10 The relation of energy density to population density, FRG [22]

thickness are the isoquants of different energy consumption and population densities. There is a fairly good correlation between energy consumption and population centres.

With the long-term and global objectives of the energy modelling effort of IIASA's Energy Systems Program in mind, it seems inappropriate to deal with the problems arising from an uneven energy density distribution by developing a full sub-regionalisation of each of the world regions. [12] But, as we argued above, these questions are important and cannot be neglected. A simplified but realistic representation of the problems related to different load densities is achieved by use of the following approach: areas of different geographic locatation and with the same range of energy/population densities are grouped together to form a small number of density classes [13] and the overall energy demand disaggregated to correspond to these classes for each of which a specific energy distribution cost figure is given. The simplest split, for example, would be a distinction between urban and rural areas, the load density in the urban area being, of course, much higher than in the rural area.

Modelling the transportion, distribution and end-use module in MESSAGE

To explain the structure of the transportation, distribution and end-use module, let us use the space heat sector as an example. Figure 11 shows its basic structure. The exogenous input to the model is the useful energy demand which, in our example, is the thermal energy needed for space heating purposes for each of the energy/population density classes described above. The useful energy demand (for space heating) can be supplied by a number of alternative space heating technologies, such as

- electric heating;
- district heating;
- gas oven; and
- solar thermal collectors;

using a variety of secondary energy forms. Then, together with the energy transportation and distribution costs of the different energy forms involved (or, in the case of solar, the national supply limitations), the share of the alternative end-use technologies in supplying the demand for space heating can be determined. The secondary energy

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[12] There are still some limits on the size of the present generation of computers and even more stringent limits on the availability of consistent data.

[13] This concept will be described in more detail later in relation to the the environmental impacts sub-model.

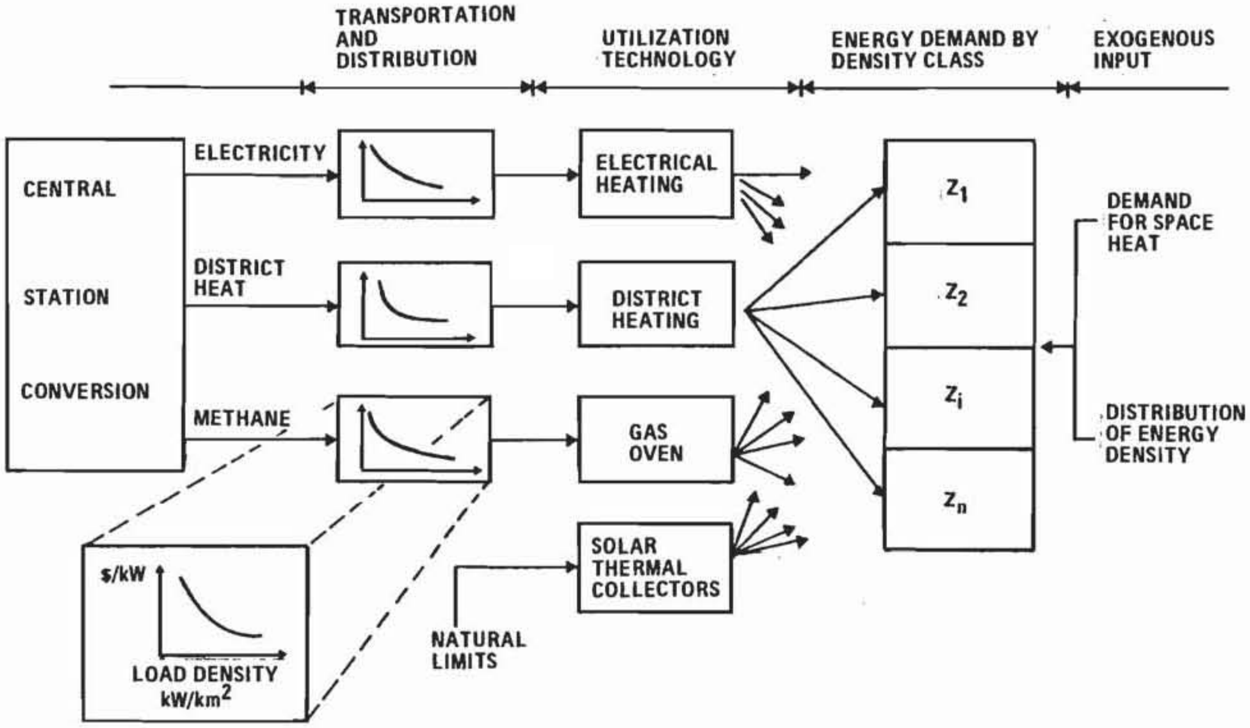

Figure 11 Structure of the energy transportation, distribution and end-use sub-model

inputs to these end-use technologies give the link to the central station conversion module which determines the optimal way of producing this required secondary energy. On the other hand, as the central station conversion module and the transportation, distribution and end-use module are both integral parts of the overall model, and therefore solved simultaneously the allocation of alternative end-use technologies in satisfying a given useful energy demand also takes into account the generation costs of the secondary energy forms.

The useful energy demand constraint has the following form:

$$\sum_{j \in n_{u_i}} u_j^r \geq z_i^r \tag{32}$$

where

u_j^r is the end-use technology j in density class r;

z_i^r is the useful energy demand i in r;

n_{u_i} is the set of end-use technologies supplying i.

One constraint is necessary for each useful energy demand category in each population/energy density class.

In the model we distinguish between three different energy consuming sectors:

- household and commercial;
- industry; and
- transportation.

Within each sector, different end-use demand categories are considered. For the residential and commercial sector these are:

- space heat;
- air conditioning;
- water heat;
- other use (cooking, appliance and lighting);

and in the industrial sector a distinction is made between:

- process heat;
- power;
- consumption for non-energy purposes.

In the case of the transportation sector, the allocation of secondary energy forms required to satisfy the demand for passenger and goods transport is given as an exogenous input, because it is very unrealistic to assume that the choice of different transportation modes (car, train, bus, etc.) is determined mainly by the specific transportation costs. There are a number of factors involved which are both irrational and difficult to quantify.

The load curves for secondary and useful energy demand

Before concluding the description of the transportation, distribution and end-use module, a remark is necessary to explain how the supply load curves for electricity and district heat are determined in the model. The mechanism can be described as follows: Each useful energy demand category is additionally described by its load characteristics. These are input values. The load curves of electricity and district heat supply are determined by the model in allocating the optimal combination of a number of possible end-use technologies (including those using electricity and district heat) to satisfy the useful energy demand of each category. The supply load curves for electricity and district heat are therefore a result of the optimisation procedure and not an exogenous input.

2.6 Environmental impacts

Energy and environmental modelling

The inter-relations between energy and the environment, the often conflicting, but sometimes complementary, objectives of securing an adequate energy supply and protecting the environment, focus attention on the need to extend the analysis of problems related to the supply of energy to include explicitly the environmental impacts of the energy supply system in the modelling scheme.

The characteristics of the energy supply problem, however, are often long-term in nature and of global consequence. It takes several years to open up a new coal field (and much longer to close an old one down if high unemployment is to be avoided). Some of the major energy importing countries, such as France, Japan and the Federal Republic of Germany, import over 70% of their primary energy needs. These important trading nations decisions on their own energy strategies have worldwide repercussions. It is exactly these long-term and global aspects of the energy problem which are the special concern of the analysis described in this paper.

But pollution does not affect the world or nations at an aggregate level. Most air pollution is a highly localized problem affecting urban regions, and water pollution is confined to specific river basins. The disposal of solid wastes and slurries competes for land with agriculture, urban development and leisure activities. Concern for the quality of the environment reinforces the arguments made earlier in respect to the distribution and end-use of energy for introducing a spatial dimension to the energy supply model. Account must be taken of

- meteorological conditions;
- settlement patterns;
- land-use; and
- topography;

if all of the environmental aspects are to be treated in detail. Figure 12 shows the interdependence of the energy system and the environment.

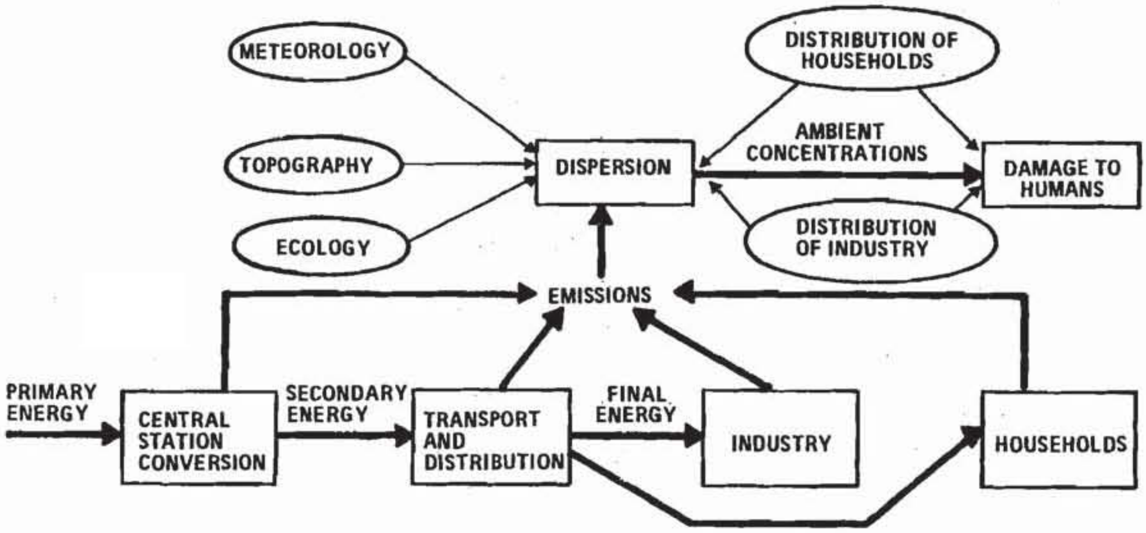

Figure 12 Energy and the environment

Clearly, though, we must not lose sight of the fact that the main concern of modelling effort of IIASA's Energy Systems Program is the examination of possible future <u>energy</u>

supply strategies. In striking a compromise between the desire to model all the many facets of the energy supply problem, including the constraints on energy supply imposed by the environment, and the necessity of limiting the model to a manageable size, it will not be possible to do justice to all aspects of the environmental pollution problem. A certain level of aggregation is inevitable but this should not be so high that the constraints that the environment imposes on the energy supply system are neglected. These constraints may prove to be more stringent than those imposed by resource or capital availability.

The impact of the energy supply system on the environment can be reduced in many ways. In theory, all of the possibilities should be reflected within the model but in practice we find that some of them lie outside the scope of MESSAGE even when included in the broad context of the energy modelling effort of IIASA's Energy Systems Program. A classification of various possibilities of achieving a reduction of environmental impacts (together with some typical examples) is listed in Table 5.

Some of these methods are aimed at reducing emissions directly (cleansing of escape gases), or indirectly (conservation of energy), while others are directed at reducing the impact of emissions (location). The complex system nature of the interaction of energy supply and the environment is illustrated by examining the possibilities for reducing impacts. Locating coal power stations away from centres of population reduces the impact of SO_2 emissions to the air but the visual intrusion of land requirements for transmission lines is increased. Additionally, energy losses in transporting electricity mean that more coal is required, increasing water pollution at the place of extraction and the amount of CO_2 discharged into the atmosphere.[14] Modern techniques for desulphurisation of escape gases are both untried and expensive. They also pose a non-trivial solid waste disposal problem.

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[14] A method for the desulphurisation of escape gases at Battersea power station, in operation as early as 1932, causes a water pollution more serious than the atmospheric pollution it was designed to resolve.

Table 5 Reducing the environmental impact of energy supply

• modification of existing techniques	• lower burning temperatures reducing NO_x (and primary effficiency)
• fuel substitution	• change to lower sulphur content coal/oil
• technological substitution	• change from fossil based technologies to nuclear or solar
• cleansing of fuel inputs	• removal of H_2S from natural gas • removal of sulphur from oil
• cleansing of escape gases	• removal of SO_2 and particulate matter from stack gases
• conservation of energy	• increasing the overall primary efficiency in the series of conversion processes from primary sources to final utilisation
• recycling of residuals	• better insulation standards • energy generation from solid wastes
• utilisation of waste heat	• district heating systems • open field agriculture
• emission substitution	• cooling towers discharging waste heat into the air instead of into waterways
• better dispersion of residuals	• building taller stacks for power plants
• location	• siting power plants, oil refineries etc. away from centres of population

Environmental pollution

The supply of energy causes many different types of negative impacts on the environment and society. These can be classified roughly as follows:

- atmospheric pollution;
- water pollution;
- land requirements;
- radio-nuclear pollution;
- solid wastes;

- occupational accidents.

The supply of energy is not directly responsible for all of these impacts but its role in many is dominant. Some 90% of atmospheric emissions of toxic substances and all thermal pollution is due to the conversion and use of energy. Water pollution from energy sources is not as important, except at the place of extraction both of fossil fuels and of natural uranium and thorium (an exception, of course, being the thermal pollution of waterways and pollution of the oceans with waste oil and from accidental spills). Since the nuclear test ban on atmospheric tests, nuclear based energy supply systems have been responsible for most of the radio-nuclear pollution from man-made sources.

If the number of pollutants is numerous, so is the manner in which they affect the environment. Generally atmospheric pollutants are toxic substances (SO_2,CO) causing damage to health, crops and material. But since they are not usually inert, their toxic effect decays due to transformation and deposition, confining the impact to the local environment around the point of emission. Some atmospheric pollutants, however, are relatively inert and their concentration will gradually build up in the atmosphere (in the case of CO_2 causing possible and serious global changes in the climate).

An indication of the scale of the effect from a selection of the most important residual discharges from energy supply systems is shown in Table 6.

Modelling the environment in MESSAGE

As we pointed out earlier, if the size of the model is not to become unmanageable, it is necessary to make some pragmatic simplifications in order to make a start in the modelling of the environmental impacts. We begin by classifying the residual discharges according to the way in which they are handled in the model. This classification reflects the relative importance of the impacts caused by the residual discharge in relation to the energy supply as well as the manner in which the impacts arise.

A toxic atmospheric emissions with local impact including short-lived radio-nuclear isotopes

- sulphur oxides;

- nitrogen oxides;

Table 6 Scale of effect of pollutants related to energy use

pollutant	local	regional	(weather)	(health)
SO_2^*	XX	X		
NO_x^*	XX	X		
CO_2				X
CO	XX			
particulates	XX	X	XX	
toxic metals	X			XX
short lived radioisotopes	XX	X		
long lived radioisotopes				XX
heat	XX	X		

- particulates;
- carbon monoxide;
- xenon 133.

B emissions of relatively long-lived radio-nuclear isotopes to the atmosphere and water whose impact will have global consequences

- tritium;
- krypton.

C the emission of CO_2.

D occupational accidents.

E all other residual discharges

- water pollution;
- thermal pollution;
- land requirements;
- solid wastes;
- atmospheric pollutants not in A above;
- radio-nuclear pollutants not in A or B above.

The emissions of groups A and B above are converted to average ambient ground level concentrations, using a simple dispersion model for the local effects and dilution factors for the global effects. A model of population distribution relates the concentrations of group A to the local population, whereas the global concentrations of group B can be expected to affect equally the entire world population.

While most climatologists agree that CO_2 emissions will change the climate, little agreement has been reached on the likely scale of these impacts, to say nothing about assessing the possible damage to man's environment which could be caused by global climatical change. Introducing constraints on CO_2 does not therefore correspond to setting standards on the level of emissions of toxic substances but only gives an idea of what it could "cost" to reduce the level of CO_2 by a certain percentage.

The residual discharges of group E are treated in the same way that we treat emissions of CO_2 but with this difference: separate subtotals are kept for (a) the central station technologies[15], (b) industry and (c) residential, commercial and transport.

Emission inventories

Normal operation of the centralised and end-use technologies, denoted by the vectors x and u respectively, is accompanied by a discharge of emissions.

Let E_x and E_u be matrices giving the emissions caused by unit operation of x and u. E_x and E_u can now be further partitioned corresponding to the 5 groups of discharges set out above. Especially in the case of group A, but also for group D, the manner of emission is of considerable importance. Since we distinguish between centralised, industrial and area discharge it is necessary to partition u into industrial and other users, $\{u^2 : u^3\}$, the index 2 denoting industrial and the index 3 area emission sources. The index 1 denotes emissions from central station conversion.

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[15] The central station technologies can be expected to control the manner in which they make discharges and also to be located in a way which minimises the environmental impact. USA standards, for instance, prevent the location of nuclear power stations within 50km of large centres of population.

The total yearly emission rates are then given by:

$$\left|\begin{array}{c} e_A^{r1} \\ e_A^{r2} \\ e_A^{r3} \end{array}\right| = \left|\begin{array}{ccc} E_{Ax} & & \\ & E_{Au^2} & \\ & & E_{Au^3} \end{array}\right| \cdot \left|\begin{array}{c} x^r \\ u^{r2} \\ u^{r3} \end{array}\right|$$

$$\left|\begin{array}{c} e_B \\ e_C \\ e_D \end{array}\right| = \left|\begin{array}{ccc} E_{Bx} & E_{Bu^2} & E_{Bu^3} \\ E_{Cx} & E_{Cu^2} & E_{Cu^3} \\ E_{Dx} & E_{Du^2} & E_{Du^3} \end{array}\right| \cdot \left|\begin{array}{c} x \\ u^2 \\ u^3 \end{array}\right|$$

$$\left|\begin{array}{c} e_E^1 \\ e_E^2 \\ e_E^3 \end{array}\right| = \left|\begin{array}{ccc} E_{Ex} & & \\ & E_{Eu^2} & \\ & & E_{Eu^3} \end{array}\right| \cdot \left|\begin{array}{c} x \\ u^2 \\ u^3 \end{array}\right| \qquad (33)$$

where

e_A^{rs}	are residuals in group A for population density class r and of emission type s (=1,2 or 3);
e_B	are relatively long-lived radio-isotopes;
e_C	is the emission of CO_2;
e_D	are the total occupational accidents;
e_E^s	are residuals in group E for emission type s.

Environmental impacts

We now show how the emissions described above can be translated into impacts to the environment.

Group A impacts: In the case of emissions of group A (SO_2 etc.), where the impacts are local or sub-regional, emissions must first be converted to ambient concentrations and the ambient concentrations then related to the population. A method for assessing the regional impact of atmospheric emissions developed at IIASA by Dennis [13] is adopted. From the emission inventory described above, we have the emissions for each population/energy density class disaggregated by emission source type. As mentioned above, the distinction is made between area sources, medium level point sources and high level sources. (See Figure 13.) The importance of making this distinction is illustrated by the estimates shown in Table 7 of the relative influence of emissions to ambient concentrations. These are much higher (a factor of 66) for low level area sources than for emissions released by high stacks.

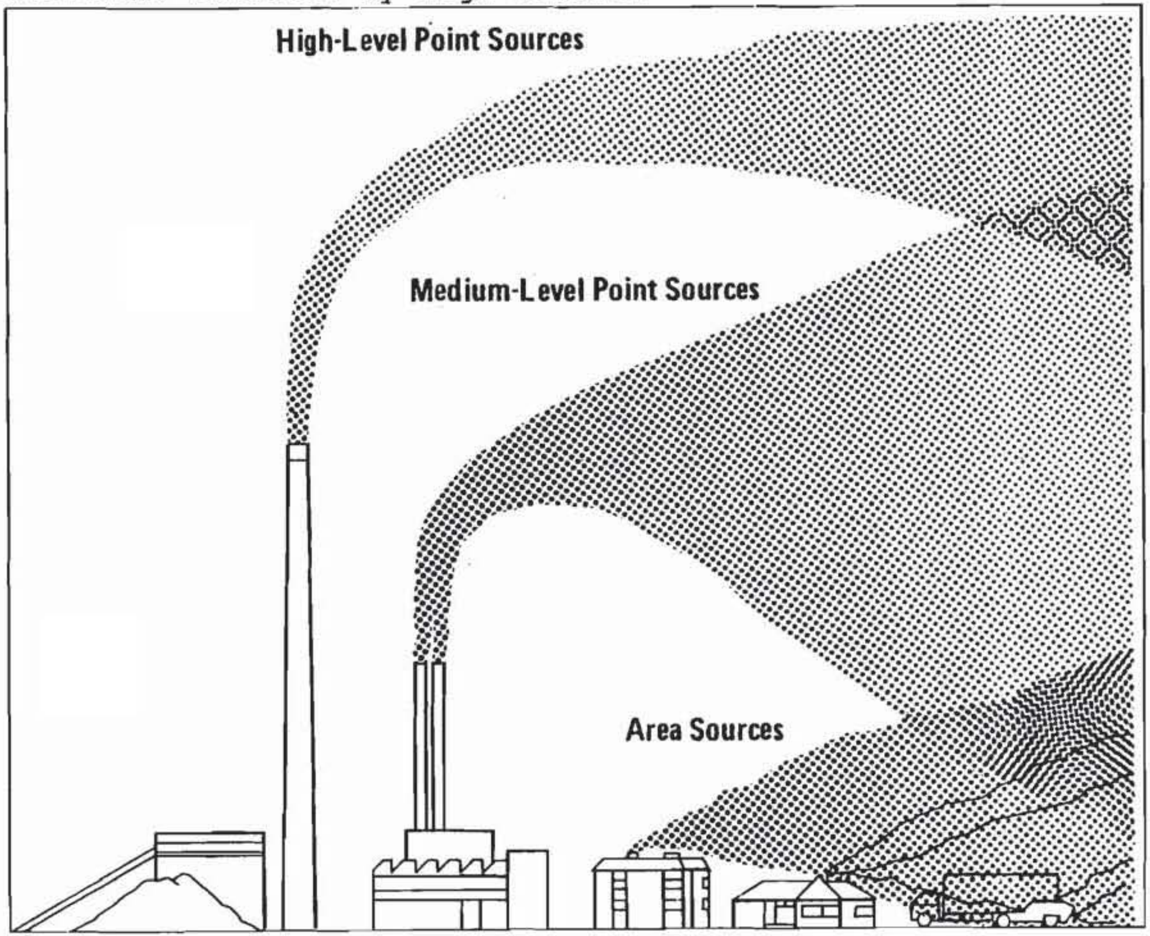

Figure 13 Emission sources

Dennis [13] suggests that a detailed dispersion model for calculating ambient concentrations is often unnecessary in assessing the regional impacts of air pollution from energy supply systems and supports this with some empirical findings for a number of North American cities. Basically his argument is that, since populations are mobile (i.e. commuting from home to work-place), average dose rates

Table 7 Relative impact of emission source on ambient concentration

source	relative influence (RI) Brookhaven estimate	 IIASA estimate (Wisconsin)
area source	7	66
medium level point source (industry)	9	14
high level source (central station conversion)	1	1

$$RI = \frac{\text{contribution to ambient SO}_2\text{ from source per unit emission}}{\text{contribution to ambient SO}_2\text{ from coal power plant per unit emission}}$$

throughout an urban area can be used. Further, he argues that a single dispersion factor for each type of emission source can be applied to total urban emissions to derive a spatially averaged ground-level air pollution concentration for the urban area.

This can be summarised as follows (for clarity of exposition, only one emission type and one finite urban area are defined):

If

e^s is the residual discharge for emission type s;

c^s is the the urban concentration due to emission source s;

d^s is the urban dispersion factor for source s;

b is the (rural) background concentration;

then the total concentration, q, is given by

$$q = b + \sum_{s=1}^{3} c^s \tag{34}$$

c^s being given by

$$c^s = e^s d^s \tag{35}$$

The implications of these findings are important. They imply that not the rate of emissions per area, but the absolute level of emissions in an urban area is the relevant indicator to use in assessing local impacts. Obviously, an urban area with a high overall population density (and therefore high emission density) will experience higher average ambient concentrations than a city of identical population (and emissions) but distributed at a lower density. Nevertheless, Dennis has only observed actual deviations of up to 10% from results of his simple dispersion model. A visual representation of the single exposure level associated with each urban area is shown in Figure 14.

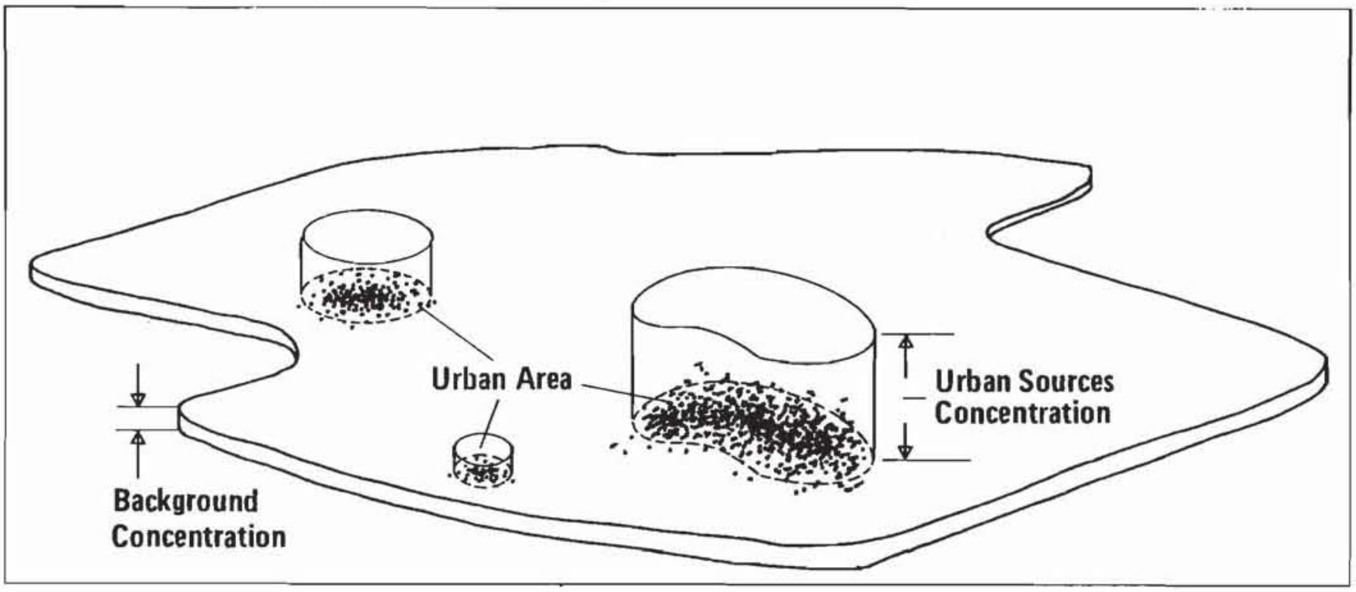

Figure 14 Smeared urban pollution concentration

The arguments set out above do not mean that population-energy-emission densities play no role in determining the level of population impact, either in our model or in reality. Large urban areas will also have a large proportion of their population living at high densities. But, in addition, we must also take account of the absolute size of urban areas. Let us suppose that the population of a region is distributed in urban areas of various sizes and that these have been ranked according to size; further, that the population of each urban area is divided into a number of classes with the same range of population density as given below

urban rank	population density				
	high	medium	low	rural	total
1	p_1^1	p_1^2	p_1^3	0	p_1^*
2	p_2^1	p_2^2	p_2^3	0	p_2^*
.	.	.	.	.	.
i	p_i^1	p_i^2	p_i^3	0	p_i^*
.	.	.	.	.	.
n	p_n^1	p_n^2	p_n^3	0	p_n^*
rural	0	0	0	p_{rural}	p_{rural}
total	p_*^1	p_*^2	p_*^3	p_{rural}	p_*^*

where

p_i^r is the population of the urban area of rank i within the population energy density class r;

* as usual denotes summation over an index.

If we assume that the level of useful energy demand is proportional to populations and that the structure of end-use technologies is the same within each density class for all cities, then we can also assume that emissions will be proportional to populations within each density class. [16] The emissions occurring in the i^{th} city within the r^{th} density class emitted from source type s is given by

$$e_i^{rs} = e_*^{rs} \frac{p_i^r}{p_*^r} \tag{36}$$

and the total emissions occurring in city i is given by:

---

[16] This is a bold simplification since some small urban areas might be heavily industrialised whereas in larger ones administration might predominate.

$$e_i^{*s} = \sum_r e_*^{rs} \frac{p_i^r}{p_*^r} \qquad (37)$$

The ambient concentration in city i is then given by applying the simple dispersion model described above:

$$q_i = b + \sum_s d^s e_i^{*s} = b + \sum_s d^s \sum_r e_*^{rs} \frac{p_i^r}{p_*^r} \qquad (38)$$

The total population impact can now be determined by multiplying the ambient concentrations of each city with the population and summing:

$$\text{impact} = \sum_i q_i p_i^* \qquad (39)$$

$$= bp_*^* + \sum_s d^s \sum_r e_*^{rs}\text{'ne5}\sum_i \frac{p_i^* p_i^r}{p_*^r}$$

There is a similar expression for each of the emissions listed under group A above.

It remains to be shown how the distribution of population in urban areas can be derived. For a small number of developed countries, statistics are available from which p_i^r, as defined above, can be taken directly. But even for the USA. this information is neither collected centrally nor readily available. See, for instance, the discussion in [14]. Not only is this sort of information even less readily available for the developing countries, but the distribution of population can be expected to change rapidly due to a shift from rural to urban areas. It is therefore necessary to develop a model of population distribution; in the case of developed countries to fill in missing data and for the developing world to model future change.

The classical model of the spatial distribution of population is that of Clark [15] who postulates that urban density declines exponentially with distance from the city centre. Its validity has often been demonstrated empirically and, recently, theoretical interpretations have been given [16]. Using this model, we can write down the total population contained within any concentric circle of radius r as:

$$p(r) = \frac{2\pi d_0}{\beta^2}[1 - (1+\beta r)\exp(-\beta r)]$$

(40)

where

d_0 is the extrapolated density at the centre; and

β is the exponential rate of decline of density with distance from the centre.

The negative exponential model of urban density gradients gives the distribution of population within an urban area; a model of the distribution of city size is necessary to complete the estimation of p_i^{ξ}. The analysis of city size distributions has shown that there is usually a remarkable rank-size regularity [17]. (See Figure 15.) This can be expressed as follows:

$$p_i = \frac{p_1}{i^{\gamma}} \qquad (41)$$

where

i is the rank of a city;

p_i is the population of the city with rank i;

p_1 is the population of the largest city;

γ is a constant.

By assuming that the distribution of cities within a region can be given by the rank-size rule and the population density within cities by the negative exponential distribution, it is possible to define the small number of population density classes for each city required for the analysis both of the environmental impacts and of the possibilities of introducing district heating.

Group B and C impacts: The buildup of radio-isotopes and CO_2 in the atmosphere is given by

$$\begin{vmatrix} m_B(t) \\ m_C(t) \end{vmatrix} = \begin{vmatrix} d_B & 0 \\ 0 & \delta_t \end{vmatrix} \times \begin{vmatrix} \sum_{\tau=0}^{t} e_B(t-\tau) \\ \sum_{\tau=0}^{t} e_C(t-\tau) \end{vmatrix} \qquad (42)$$

where

d_B is the decay factor over the period δ_t (related to the half life of the radio-isotope);

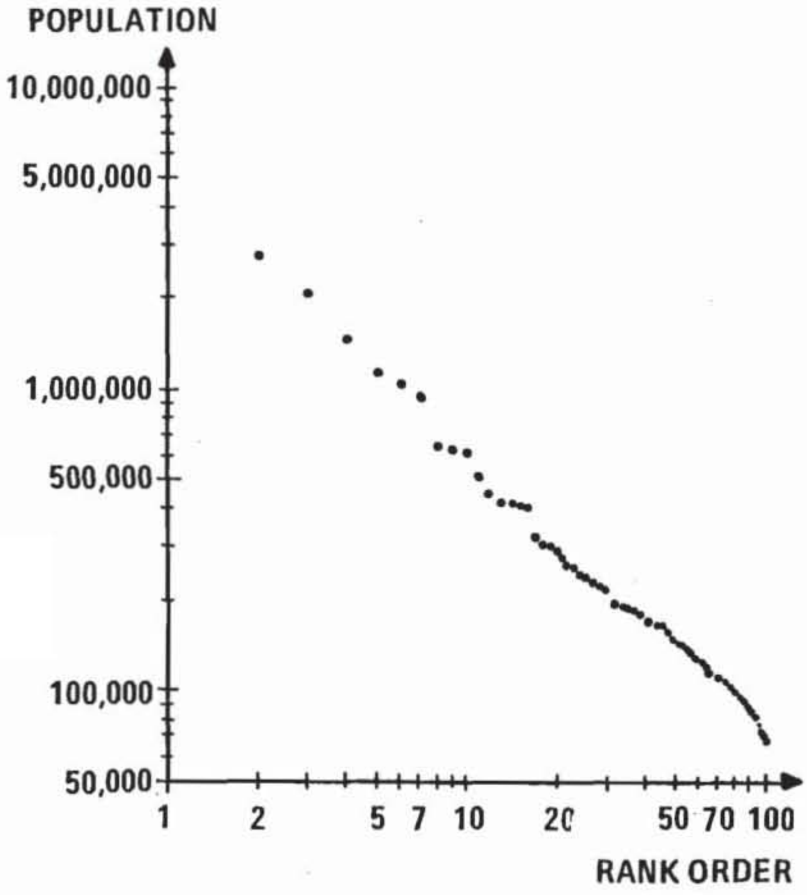

Figure 15 Rank ordering of standard metropolitan areas in England [23]

$m_B(t)$, $m_C(t)$ are the amounts of pollutants B and C at time t.

The vector $m_2(t)$ is related by the dilution factors s_a, s_w to ground level atmospheric and surface water concentrations respectively to give us the the environmental impacts (in physical terms) which can now be written down as follows:

Group B impacts must be divided into two sub-sections, namely the concentration of radio-isotopes in air and water:

a) the concentration of radio-isotopes in surface water (Ci/cm^3) which is given by Beller [18]^{17}

$$\text{impact(water)}_B = s_w' m_B(t) \quad [\text{Ci/cm}^3] \tag{43}$$

b) the atmospheric concentration of radio-isotopes at ground level (Ci/cm^3) given by

$$\text{impact(air)}_B = s_a' m_B(t) \quad [\text{Ci/cm}^3] \tag{44}$$

Group C impacts: The tons of CO_2 in the atmosphere, are given by

$$\text{impact}_C = e_C(t) \qquad [\text{tons}] \tag{45}$$

Group D impacts: The number of occupational accidents, are given by

$$\text{impact}_D = e_D(t) \qquad [\text{number of accidents}] \tag{46}$$

Group E impacts: The atmospheric impacts not included in groups A and B, are given by

$$\text{impact}_E = e_E^S \qquad [\text{tons}] \tag{47}$$

Abatement technologies for reducing atmospheric pollution

Several methods are available or are being developed to reduce the discharge of residuals from fossil fuels. The importance of these techniques is likely to increase over the next few decades as the gas and oil reserves run out and dependency on coal for fossil fuel increases. Without the introduction of abatement procedures, the OECD [19] have estimated that the projected emissions of sulphur and nitrogen oxides will almost double during the period 1968-1980. Even if the nuclear option is taken and its development accelerated, the importance of coal as a major source of energy is more likely to increase than decrease; without abatement techniques, so will the damage caused by SO_2.

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[17] He gives a dilution factor for tritium of $4.3*10^{24}\text{cm}^3$ is given, which assumes dilution to a depth of 75 cm in oceans and atmospheric and surface water. For Kr-85, a diluting mass of $4.3*10^{24}\text{cm}^3$ of air is given.

A list of some technological methods (abatement is too narrow a term) for reducing residual discharge includes the following:

- fuel substitution;
- particulate collection, flue gas scrubbing and desulphurisation;
- desulphurisation of oil (residuals and distillates) and mechanical desulphurisation of coal;
- fluidised bed combustion of coal;
- gasification and liquefaction of coal.

Fuel substitution

At least 80% of the known coal reserves of the USA are of medium to high sulphur content. Thus in view of SO_2 emissions, fuel substitution is not a major option (at least for the U.S.A.) except in the short term while natural gas reserves and low sulphur crude oils are still available. The possibilities are greater in Europe where the coal reserves generally have a lower sulphur content than residual oil, but as standards are tightened these too will be in great demand and short supply. Substitution alone should not alleviate the overall sulphur emission problem.

Cleansing of stack gases

Particulate collection: It is technically feasible to remove over 99% of particulates and although the costs involved - both capital and operational, but especially solid waste disposal - are substantial, they are small in comparison to fuel costs and generating equipment. In MESSAGE it is assumed that all centralised conversion technologies will use devices which remove at least 90% of solids (i.e. using electrostatic precipitators).

Desulphurisation of flue gases: These can be classified as throwaway or recovery techniques. In throwaway techniques, the sulphur oxides are converted into various sulphates and sulphites which are then disposed of as waste material. Recovery systems produce either sulphur or sulphuric acid both of which have a commercial value.

At the present time three methods look most promising

- wet lime/limestone scrubbing;
- wet magnesium oxide (MgO) scrubbing; and
- catalytic oxidisation (CAT-OX).

Wet lime/limestone scrubbing is at present the most developed process. It uses lime or limestone to absorb the sulphur oxides, the end product being large quantities of liquid sludge. The disposal of this sludge poses very serious waste disposal problems. Magnesium sulphite, which is also produced, is soluble in water and could leach into ground water. A reduction of about 90% of sulphur oxides, 99% of particulate matter and 20% of nitrogen oxides can be expected by lime/limestone scrubbing.

Wet magnesium scrubbing and catalytic oxidation processes are more attractive since a commercial product - sulphuric acid - is the ultimate by-product, thus avoiding the waste disposal problem. The process is generally expected to be more expensive than lime/limestone scrubbing. The cost of these systems is estimated to be around 2-4 mills/kWh. [20]

Desulphurisation of oil and coal

By-product recovery from or cleansing of the stack gases is a viable alternative only for large centralised processes. In the absence of district heating systems (i.e. for areas with low energy densities), the use of fuel oil, and in some cases coal, to provide space and water heating for residential and commercial consumers is likely to retain an important role. But as was pointed out earlier, the contribution of decentralised area sources of emissions to ambient concentrations is much higher than for centralised plants. In taking this into account it can be seen that the emissions of these decentralised technologies should receive special attention. The only practical way of controlling these emissions is to impose input standards on the quality of fuel.

Desulphurisation of crude oil: Desulphurisation is now becoming standard practice in many countries, residual fuel desulphurised to 1% sulphur by weight being assumed by most countries. The cost of achieving this is dependent on the sulphur content of the crude oil.

The main desulphurisation techniques - commercially proven processes - involve hydrogen reacting with sulphur in the presence of catalysts. In some processes the residuum is vacuum-distilled and the distillate desulphurised to less than 0.1% sulphur. This oil is then back-blended to give a product of the desired sulphur content. The ultimate by-product is elemental sulphur.

Desulphurisation of coal: By mechanically desulphurising coal it has been shown that there are many reserves of coal which can be deep cleaned to less than 1% pyritic sulphur content by weight. Ferrell concludes that this process [21] is attractive for the USA, especially when used in combination with partial flue gas cleaning.

Fluidised bed combustion and combined cycles

These processes - not so much abatement techniques but rather new technologies - consist of burning fuel (coal or fuel oil) on a non-combustible bed consisting of limestone or dolomitic particles. Upwards of 90% of the sulphur in the fuel is retained in the bed and due to lower combustion temperatures there is also a reduction in the emission of nitrogen oxides.

Gasification and liquefaction of coal

The gasification (and liquefaction) of coal, possibly in combination with process heat from nuclear reactors, has already been mentioned. Both sulphur and particulates can be removed from the smaller volume of gas more economically than from the larger volumes of combustion flue gas. Not only is the sulphur content per calorific value lower, but higher conversion efficiencies are generally achieved by using gas rather than coal.

Abatement in MESSAGE

Generally, abatement technologies are included in MESSAGE by defining a new conversion technology for each abatement technique considered. For instance, in addition to a conventional coal power plant we define a coal power plant with limestone scrubbing. Theoretically we could define as many new techniques as there are abation techniques. In practice, only the most promising technique for each conventional conversion technology is included in the model plus the new technologies such as fluidised bed combustion and combined cycles.

A different approach is adapted for the desulphurisation of fuels and the technologies which use either these "cleaned" or synthetic fuels. A desulphurisation technology can be defined which takes natural fuel as the input and produces fuel with lower sulphur content. Since the same conversion technology can use either the clean or dirty fuel, a similar approach can be adopted to the way in which the joint production of electricity and district heat is modelled, i.e. two modes of operating the plant are defined, one mode using dirty, the other clean fuel input. Allowing for this possiblity is, of course, especially important in the decentralised conversion and end-use sector where the contributions to ambient concentrations are very much higher relative to emissions.

Environmental constraints

Generally the impacts outlined above can be constrained below some desired maximum (standard) or, suitably weighted, they can be included in the objective function. Both possibilities imply that heroic value judgements be made. Since no two people will agree on the valuation of such things as the "value" of life the only approach possible is to carry out extensive sensitivity analysis around the cost optimal minimum. As the environmental constraints are tightened (or the weights in the composite objective function increased) either abatement controlled technologies are drawn into the solution or there is a move from "dirty" to "clean" technologies.

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APPENDIX: Glossary of terms

Primary energy	The energy occuring naturally, both renewable resources such as solar radiation and non-renewable resources such as fossil and fissionable material.
Secondary energy	Refined and/or converted primary energy (e.g. electricity and gasoline produced from coal and crude oil, respectively) but also non-converted primary energy that can be used directly by the final user.
Final energy	The secondary energy remaining after transmission, storage and distribution which is delivered to the final user. Final energy is then converted by end-use (i.e. local conversion) devices to satisfy the demand for useful energy.
Useful energy	The energy in terms of useful heat, light, mechanical power, etc. needed to provide a level of service to the final user, e.g. the heat required to warm a room or the mechanical power required to turn a lathe.
Load region	The level of demand for energy exhibits periodic fluctuations, both seasonal and daily. The load region is the fraction of the time period during which the demand for energy is taken to be constant, i.e. the load regions will be typically labelled as peak, intermediate and off-peak.
Load density	The ratio of energy demand to area, which is closely related to population density or the intensity of industrial activity per area.