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A METHODOLOGY FOR REGIONAL ENERGY SUPPLY OPTIMIZATION

H. Stehfest

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Preface

This report is one of series describing a multidisciplinary multinational IIASA research study on Management of Energy/Environment Systems. The primary objective of the research is the development of quantitative tools for energy and environment policy design and analysis -- or, in a broader sense, the development of a coherent, realistic approach to energy/environment management. Particular attention is being devoted to the design and use of these tools at the regional level. The outputs of this research program include concepts, applied methodologies, and case studies. During 1975, case studies were emphasized; they focused on three greatly differing regions, namely, the German Democratic Republic, the Rhône-Alpes region in southern France, and the state of Wisconsin in the U.S.A. The IIASA research was conducted within a network of collaborating institutions composed of the Institut für Energetik, Leipzig; the Institut Économique et Juridique de l'Énergie, Grenoble; and the University of Wisconsin, Madison.

Other publications on the management of energy/environment systems are listed in the Appendix at the end of this report.

Wesley K. Foell

Abstract

This paper presents the essential features of a model for regional energy supply optimization. The approach proposed in the paper differs significantly from other models dealing with similar problems. These models are in most cases linear optimization models with a single attribute objective function (usually costs); other aspects such as the impact on the environment, are included in the form of constraints. The method described here attempts to include simultaneously several attributes of a certain energy supply strategy related to its economical and ecological consequences in a multiattribute utility function, which is then used as the objective function of the optimization model.

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1. Introduction

Among the most important decisions taken by any legislative or administrative body are the decisions on energy policy, because energy is a major driving force of almost all economic activities. Accordingly there have been many attempts at building more or less sophisticated tools to facilitate and rationalize the decision-making process on energy policy. They range from simple extrapolation techniques over simulation models [5,11] and input-output models [8] to optimization models, which mainly deal with optimization of energy supply at given demand [4,6,7,10]. The optimization models quoted have two major deficiencies, which were the motives for the work in hand:

Firstly, their objective functions do not include environmental impacts, although decisions on the energy system ought to be the result of a trade-off between economic and environmental impacts. In some cases constraints for certain pollutant emissions are imposed, but emission values are not very meaningful in evaluating environmental impacts, and the resolution of environmental-economic trade-offs by varying environmental constraints is a tedious process, which does not make very clear the actual preferences of the decision-maker.

Secondly, the supply optimization models are not very well suited for application to a relatively small region with its many links to other parts of the same country. The ideal case for those models is a large, completely selfcontained, and homogeneous country.

Therefore, the goal of this work was to develop a supply optimization model which can handle the economy-environment trade-offs explicitly and which is applicable on a regional level. As in [7] and [10], much attention was to be paid to the substitutability of the different energy forms within the demand sectors. The optimization was to be done for a time period of 50 years.

2. General Description of the Approach

Decisions concerning the energy supply system of a region have, in general, many consequences, all of which have to be taken into account simultaneously, if one is to find the "optimal" decision. Subjective judgement will be inavoidable during the decision process, in particular as far as the weighting of the various consequences is concerned. A rational way of decision-making under these circumstances is the use of multiattribute utility functions [9]. The so-called attributes, which are the independent variables of those functions, measure one or several classes of consequences of the decisions under discussion. An attribute related to energy policy decisions could be, for instance, the SO_2 concentration, which could be a measure of all impacts of SO_2 on human beings and objects. The utility function expresses the degree of satisfaction of a person for all possible combinations of attribute values, and in case of uncertainty about the attribute values the expected value of the utility function is the criterion for the choice among the decision alternatives. This means, the maximization of the expectation of his utility function is what the decision-maker should want, if he wants to be logically consistent with his preference structure. The utility function can be assessed by means of a sequence of relatively simple questions to the decision-maker [1,9]. Thereby the decision-maker's own understanding of his problem is greatly improved. Considering all these characteristics, the multiattribute utility theory approach seems to be very suitable for the supply optimization problem. Therefore, the objective function to be maximized is assumed to be a multi-attribute utility function.

The model of the regional energy system which is used for the supply optimization is shown schematically in Figure 1. Energy contained in primary energy resources P_i is converted into intermediate energy forms I_k which in turn is used by different demand sectors D_ℓ. The essential variables of the problem are the yearly energy flows x_{jik} and $y_{jk\ell}$ and the corresponding capacities Δx_{jik} and $\Delta y_{jk\ell}$ to be built in the same years. There are, in general, more than one flow between one and the same P_iI_k - or I_kD_ℓ - pair which differ with respect to environmental protection expenditure for the conversion process or with respect to location of the process (e.g. inside or outside the region). But instead of having more than one flow between one pair, one could raise the number of primary energy, secondary energy and demand categories appropriately. The subscript which ought to be used for distinction between flows in case of multiplicity is left out in the following if there is no ambiguity. In principle, one could dispense with the intermediate energy categories and look directly on all admissible flows between P_iD_ℓ - pairs. This would increase the number of variables, which is a disadvantage for optimization, but on the other hand one would have a few less constraints for the optimization (see Section 6), which is beneficial. The scheme in Figure 1 was chosen because it seems to be clearer and easier to manipulate.

The whole set of flows which are taken into account for the regional energy supply optimization are shown in Tables 1 and 2. Solar energy is assumed to be converted into electricity through photo-voltaic cells only. The synthetic fuel is treated as if it was hydrogen. Use of off-peak electricity for pumped storage and synthetic fuel production are looked upon as demand categories, and the stored energy is fed back to the primary energy side. Alternatives for pollution abatement measures are considered only for conversion and not for consumption processes. For cooling of electric power plants, only wet and dry cooling towers are considered. And not more than two alternatives for the location of the conversion processes are assumed.

One can see from Tables 1 and 2 that the number of variables of the supply optimization problem is very high if the optimization is to be done over several time periods. The same applies to the number of constraints. Therefore the only optimization technique which can be applied at reasonable computational effort is linear programming. This means the optimization problem has to have the following form:

$$\text{Maximize } A^T X + B^T \Delta X + C^T Y + D^T \Delta Y = U(X, \Delta X, Y, \Delta Y) \qquad (1)$$

$$\text{subject to } E_k^T X + F_k^T \Delta X + G_k^T Y + H_k^T \Delta Y \gtreqless R_k \ , \quad k=1,\ldots k, \qquad (2)$$

$$X \geqslant 0, \quad \Delta X \geqslant 0, \quad Y \geqslant 0, \quad \Delta Y \geqslant 0, \qquad (3)$$

where X, ΔX, Y, ΔY are vectors composed of all x_{jik}, Δx_{jik}, $y_{jk\ell}$, and $\Delta y_{jk\ell}$, respectively, and A, B, C, D, E_k, F_k, G_k, H_k are constant vectors of appropriate length. This means, the utility function has to be a linear function of flows and capacities. It is described in detail in Section 3. The constraints , which guarantee in particular, that the given demands are met, are discussed in Section 5.

For an optimization on a regional scale, single conversion or consumption installations may be relevant. Therefore, it may be necessary to impose some integer constraints in addition to (2) and (3) which guarantee reasonable plant sizes:

$$\Delta x_{jik} = 0 \bmod s_{ik}, \quad \Delta y_{j'i'k'} = 0 \bmod t_{i'k'} \qquad (4)$$

for some j, j', i, i', k, k'.

In cases where energy flows differ only by the pollution abatement effort, it may be reasonable to put the sum of the corresponding capacities on the left-hand side of the constraints, which means that the abatement effort can be varied continuously between the two extremes given in Table 1. With the additional constraints (4), the supply optimization problem is a mixed integer-linear programming problem. The computational solution of it is discussed in Section 7.

3. The Objective Function

In general, the actual utility function $U(X, \Delta X, Y, \Delta Y)$ is a non-linear, non separable function, and the problem arises how to approximate it by a linear function of the kind (1).

First of all the impacts should be aggregated into attributes α_i in such a way that they are preferentially independent and utility independent [9], which is, in general, possible. Then either [9]

$$U(\alpha_1, \dots \alpha_N) = \sum_{i=1}^{N} k_i u_i(\alpha_i) \qquad \text{or} \qquad (5)$$

$$1 + kU(\alpha_1, \dots \alpha_N) = \prod_{i=1}^{N} (1 + kk_i u_i(\alpha_i)), \qquad (6)$$

where $\quad 0 < k_i < 1, \qquad 1 + k = \prod_{i=1}^{N} (1 + kk_i)$, and

U and u_i are scaled from zero to one.

If U is of form (5), a linear objective function (1) is obtained by linearizing all single attribute utility functions u_i.

If (6) applies, quite often k is close enough to zero so that (5) can be used as an approximation to (6). If (5) is not a good approximation to (6) one can use the linear functions which describe the tangent planes of U (as a function of u_i) in a search technique (see, for instance, [12]), which uses linear programming for each search step. One can also narrow the admissible ranges for some of the attributes, which increases the chance of (5) being the appropriate from. But this means that additional constraints have to be introduced (see Sect. 5), which might even make the problem insoluble (no feasible solution).

The single attribute utility functions u_i in most cases come out from the assessment process as linear functions. If nonlinearities are relevant, they are in most practical cases such that the function is concave (see Fig.2), since concavity indicates risk aversion. Then for the optimization a polygon approximation to the function can be used without relevant loss of efficiency [2]. (The number of variables and constraints thereby is raised by the number of edges of the polygon approximation). If a utility function becomes convex, the application of linear programming is difficult. But again one could do with narrowed ranges of the attributes, which make a linear approximation more reasonable.

Finally, in order to have a linear objective function, the attributes have to be linear functions of the components of X, ΔX, Y, ΔY. This is in practice always well fulfilled if the plant sizes for each flow are assumed to be fixed.

4. The Attributes

The attributes selected for the regional energy supply optimization are listed in Table 3 along with a short description. The maxim behind this choice was to cover with the attributes the consequences of energy conversion and consumption as far as they are not controversial. Those parts of the series of consequences which depend on subjective judgements should be decided on by the decision maker through his utility function. One can, for instance, relatively accurately estimate the increase in SO_2 concentration due to combustion of oil and coal, but it is hard to predict what this means with regard to human life time; therefore the SO_2 concentration increase was chosen as an attribute rather than additional deaths. If "additional deaths" was used as an attribute the subjective probabilities for additional deaths due to increased SO_2 levels would have to be assessed also because the expectation of the utility is the criterion to be maximized. Since this will most likely puzzle the decision maker, such attributes have been avoided. (In addition, decision makers are usually reluctant to make explicit their preferences between human lives and economic quantitites which would be necessitated by an "additional deaths" attribute). In either case a detailed discussion of possible consequences of increased SO_2 levels is necessary before the assessment.

Another important aspect for the choice of the attributes was to take into account the differences between those regions which are relevant for meeting the energy demand of the region investigated. Differences to be considered exist, for instance, with regard to air pollutant dispersion characteristics, or with regard to population density and distribution. In principle one could define two different attributes for the same kind of impact in two different regions. But in order to keep the problem easy to survey, impacts of the same kind in all regions considered were aggregated into one attribute. However, in assessing the utility function of a decision maker one has to be very flexible as to the attributes. Usually the kind and number of attributes change in the course of the assessment procedure.

The attributes listed in Table 3 cover mainly impacts on human beings. This means that attributes which can be looked upon as an ambient concentration are weighted with population density; they are named "exposures". If α_i' is the level of one of those attributes, the total impact attached to α_i' is the same as if all people in the region investigated were exposed to the ambient concentration α_i' , given that the dose-effect relationship is linear. This reflects the fact that impacts outside the region have the same weight as inside.

In principle, the attributes for different years have to be treated as different attributes and the decision maker's preference over the years can be assessed in the same way as over different attributes. A simpler approach to the problem, which is followed for the present, is to assess a discount rate for each of the attributes.

Those levels of attributes which depend on atmospheric dispersion are calculated in the following way: Assuming isotropic wind, the ground level concentration C(R) at distance R from a point source can be calculated approximately from the following formula [3]:

$$C(R) = \frac{q}{2\pi\bar{u}H} f_z(R) e^{-\lambda\frac{R}{\bar{u}}} \qquad (7)$$

where:

q = source strength,

$\bar{u}$ = mean wind velocity,

H = thickness of dispersion layer,

λ = residence time of the material in the atmosphere,

f_z = ratio between ground level concentration and vertical mean value of concentration, which is analytically known.

The concentration which the population of a region is exposed to is calculated using an expression for the concentration within a uniform area source, which is an integration over (7). Two kinds of area sources were considered: emissions which are attached to human settlements are considered as area sources of the same size as the cities, all other emissions are assumed to be distributed uniformly over the whole region. (In calculating the concentration in cities of a certain size, all other settlement emissions contribute to the background as if they were distributed uniformly over the whole region, too.) One can, of course, use more sophisticated methods for the calculation of the ambient concentration, as long as no site specific characteristics of the emissions are to be taken into account.

5. Constraints

The constraints of type (2) which are used for the energy supply optimization are listed in Table 4. Most of them are self-explanatory. Constraints of type 5 say that a new technology can only be introduced at a limited rate, which depends on how much is already invested with this new technology in the past.

Constraints of type 7 are derived in the following way: Assume that the load factor for an intermediate energy i (e.g. electricity) be λ_o, irrespective of the total amount of energy. If now capacities of off-peak users (i.e. users which can use intermediate energy i at any time, e.g. electric cars, pumped storage etc.) are installed, the load factor increases as a function of the total off-peak user capacity according to the curve shown in Fig. 3. The curve, which gives an upper limit for the amount of intermediate energy i, is always concave. Therefore, the constraint which is represented by the curve in Fig. 3 can be approximated by those linear constraints of type 7 and one of type 4, which are represented by four straight lines in Fig. 3. By means of these constraints the introduction of off-peak users can be investigated without having different load categories, which would increase the size of the problem considerably.

6. Inputs

The input data, which were already dealt with implicitly in Chapters 3 through 5, can be arranged in three groups, which define

- the initial situation,
- the internal structure of the energy supply system,
- the policy variables to be investigated.

The initial situation is given by the existing capacities for all energy flows and the age of those capacities.

The second group comprises costs, efficiencies and environmental impact data of the energy flows. Other data which are relevant for the structure of the energy systems are the life times of the installations, the load characteristics, and the plant sizes.

Input data which reflect policy issues are the sectoral energy demands (as functions of time) and the coefficients of the utility function. Constraints for supply of basic fuels and for growth of capital stocks for certain conversion processes are also to a large extent subject to political decisions.

7. Computational Aspects

The optimization model is applied for a time period of 50 years, which is divided into 10 steps. Then the number of variables is ≈ 1700, the number of constraints is ≈ 1200, including the integer constraints (but not constraints of type (5), of course). This means that it is already a fairly large problem. The MPSX package of IBM is being used, which has an option for Mixed Integer Programming. It is questionable whether the optimal solution of the problem will be reached within a reasonable time. But since it is a branch and bound algorithm one can stop at any time and get a suboptimal solution, which can be compared with the solution of the simple linear problem (without integer constraints), which gives an upper bound for the optimal value of the utility function.

8. Applications and Extensions

The methodology described will be applied to Baden-Württemberg, which is one of the federal states of West Germany. This is carried out in close connexion with the decision makers who are responsible for energy policy on the federal state level. The supply optimization model is intended to become a tool for those decision makers which allows, in particular, to rationalize the economy-environment conflict resolution and to study the sensitivity of the optimal solution to variations of the policy variables mentioned in Chapter 6.

The approach described is also to be extended methodologically into several directions. The main problems are to make energy demands subject to the optimization, and to use social preference functions as objective functions, which are aggregated from individual preference functions. Another problem is the balancing of the optimizations of different regions. If several regions optimize their energy supply systems separately, the results may look inefficient from a higher level point of view. Simultaneous optimization of all regions usually is unfeasible because of high dimensionality. Perhaps an iterative algorithm can be developed which smoothes out inconsistencies between different regions.

Acknowledgement

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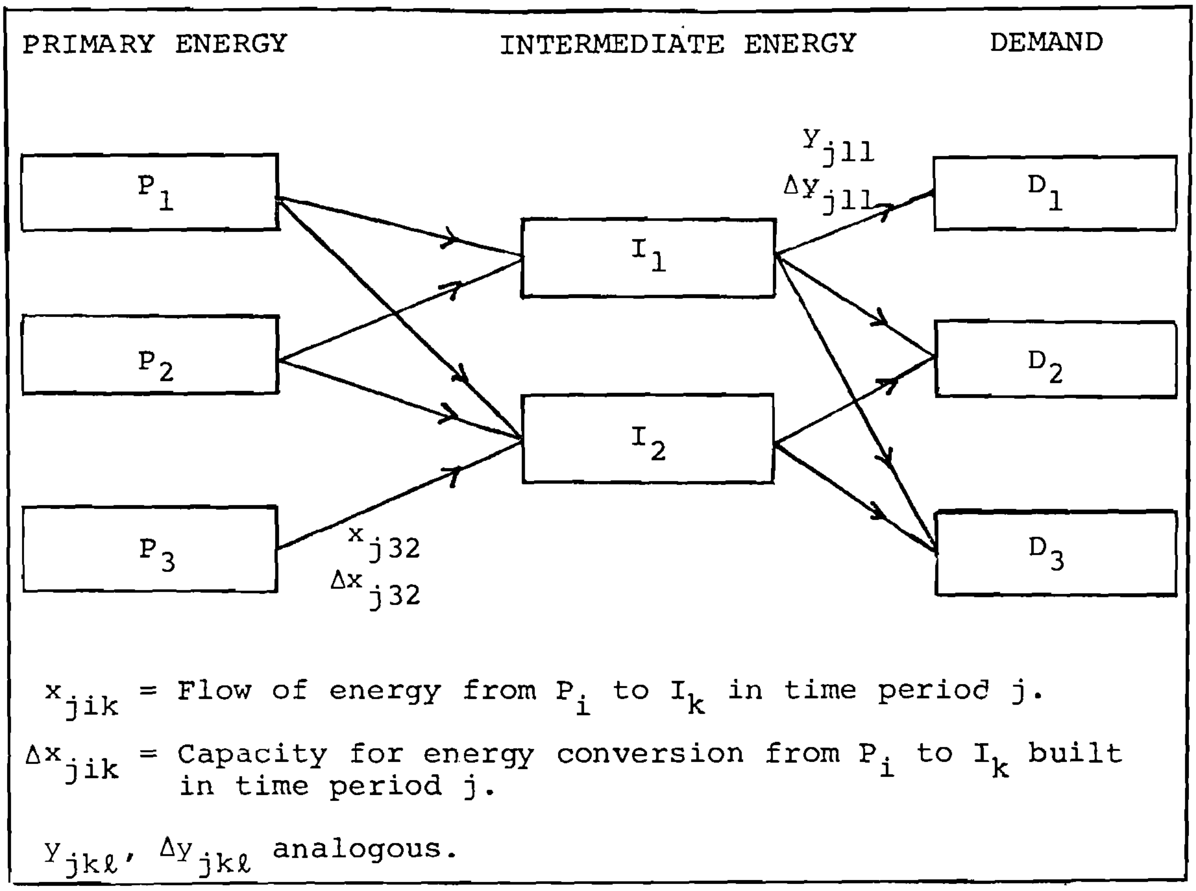

Fig 1: Scheme of Energy Supply System

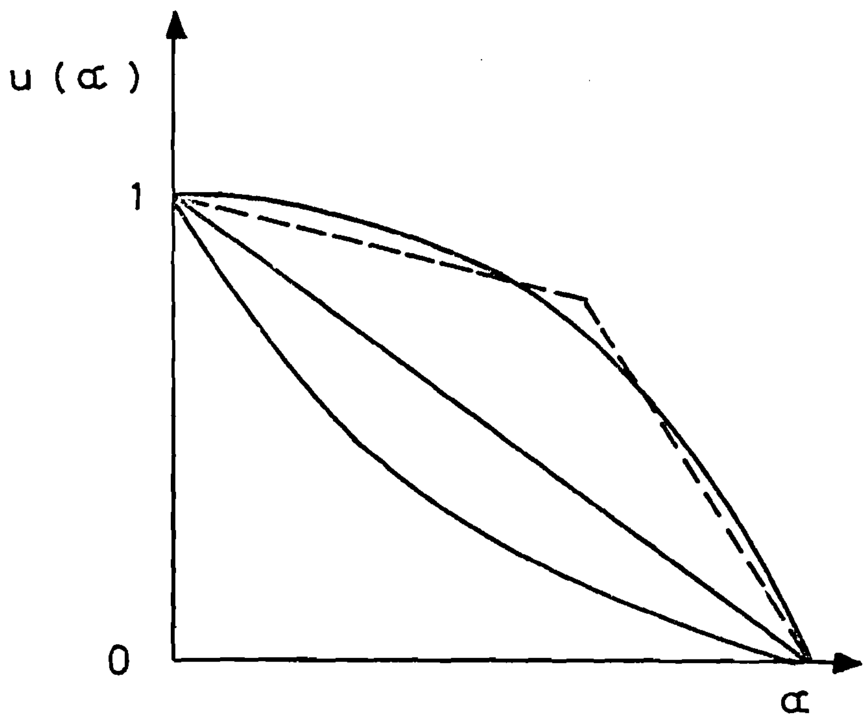

Fig. 2: Types of Utility Functions

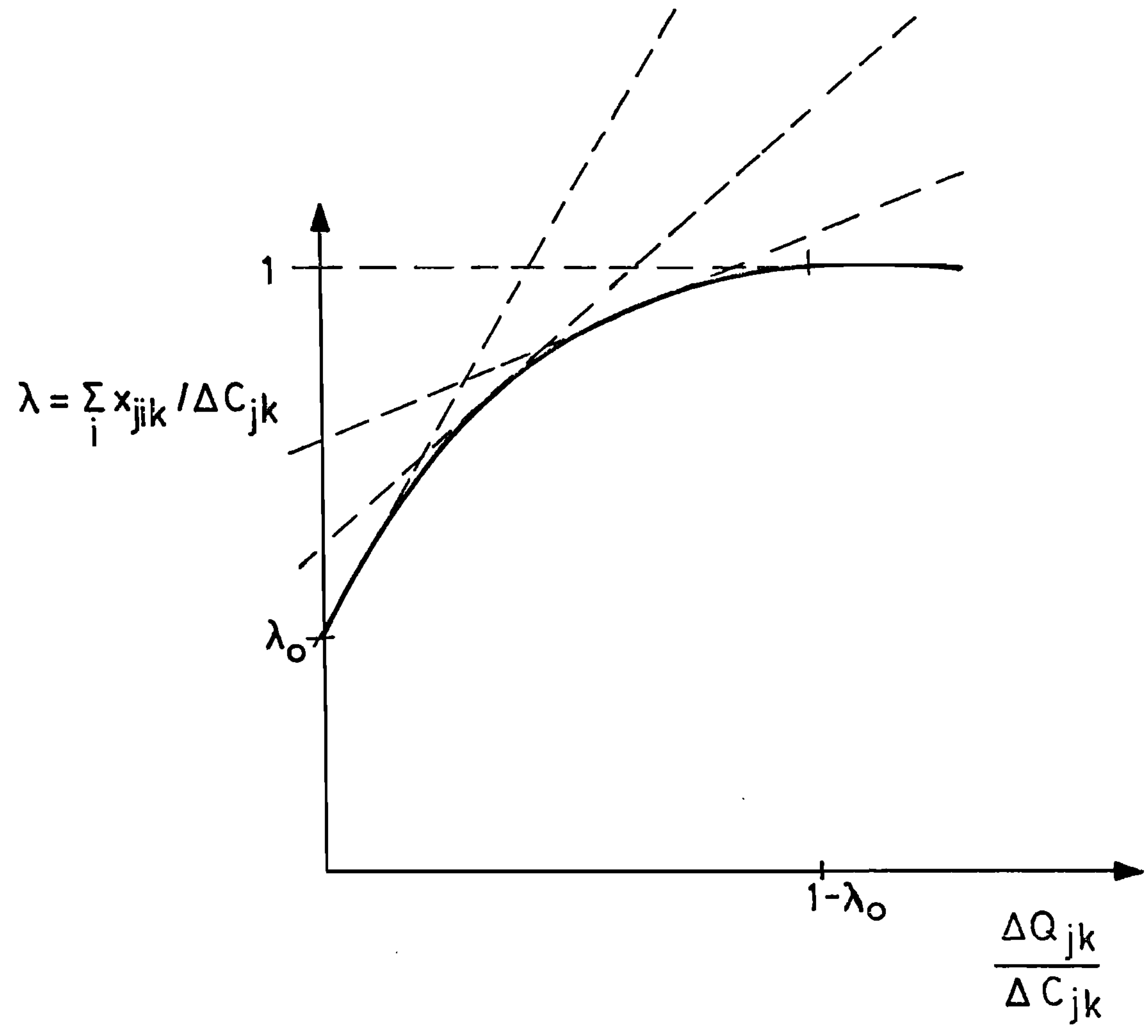

Fig. 3: Dependence of Load Factor λ on Capacity of Off-Peak Users.

Intermediate Energy \ Primary Energy				Coal	Oil	Gas	LWR	LMFBR	HTGR	SOLAR	Pumped Storage	Synth. Fuel from Off-peak Elec.
ELECTRICITY	INSIDE	without abatement	dry c.	x	x	x	x	x	x	x		
			wet c.	x	x		x	x	x			
		with abatement	dry c.	x	x		x	x	x			
			wet c.	x	x		x	x	x			
	OUTSIDE	without abatement	dry c.	x	x	x	x	x	x	x		
			wet c.	x	x		x	x	x		x	
		with abatement	dry c.	x	x		x	x	x			
			wet c.	x	x		x	x	x			
HEAVY OIL PRODUCTS	INSIDE	without abatement			x							
		with abatement			x							
	OUTSIDE	without abatement			x							
		with abatement			x							
LIGHT OIL PRODUCTS	INSIDE	without abatement			x							
		with abatement			x							
	OUTSIDE	without abatement			x							
		with abatement			x							
SYNTHETIC FUEL	INSIDE	without abatement							x			
		with abatement							x			
	OUTSIDE	without abatement							x			x
		with abatement							x			
LOW TEMPERATURE HEAT		without abatement		x	x		x	x		x		
		with abatement		x	x		x	x				
GAS	INSIDE			x		x						
	OUTSIDE			x		x						
COAL	INSIDE			x								
	OUTSIDE			x								

TABLE 1. ENERGY CONVERSION FLOWS.

Abbreviations

LWR = light water reactor

LMFBR = liquid metal fast breeder reactor

HTGR = high temperature gas cooled reactor

c. = cooling

DEMAND CATEGORY / INTERMEDIATE ENERGY	Space & Water Heat-ing	Air Condi-tioning	Trans-porta-tion	Primary Metals Ind.	Services & Households (except space & water heating)	Construc-tion Mater-ials Ind.	Chemical Ind.	Misc. Ind.	Pumped Storage	Synthetic Fuel from Off-Peak Electricity
Electricity	X	X	X	X	X	X	X	X	X	X
Heavy Oil Products	X			X		X	X	X		
Light Oil Products			X							
Synthetic Fuel	X	X	X	X		X	X	X		
Low Temp. Heat	X						X			
Gas	X			X		X	X	X		
Coal	X			X		X	X	X		

Table 2 ENERGY CONSUMPTION FLOWS

TABLE 3. LIST OF ATTRIBUTES FOR REGIONAL ENERGY SUPPLY OPTIMISATION.

1. Cost of energy supply (\$/cap)
2. SO_2 exposure ($\mu g\ SO_2/m^3$)

   Evaluation:

   $$\alpha_2 = \frac{1}{p_0} \sum_i \int_{A_i} p(\bar{x}) \Delta\sigma(\bar{x}) d\bar{x},$$

   where i = index for the regions which are considered for energy production with SO_2 emission,

   $\bar{x} = (x_1, x_2)$ = location,

   A_i = area of region i,

   p = population density,

   p_0 = population of the region under investigation,

   $\Delta\sigma$ = SO_2 ground level concentration due to the energy system of the region investigated.

   Attached impacts:

   Early death, respiration diseases, destruction of monuments.

3. Relative humidity exposure (% decrease of saturation deficit)

   Evaluation:

   $$\alpha_3 = \frac{1}{p_0} \sum_i \int_{A_i} p(\bar{x}) \frac{100}{100-\phi(\bar{x})} \Delta\phi(\bar{x}) d\bar{x},$$

   where ϕ = natural relative humidity,

   $\Delta\phi$ = increase of relative humidity due to the energy system of the region investigated.

   Attached impacts:

   Increase of clouding, icing, fogging and humidity

TABLE 3 continued.

4. Radiation exposure (rem)

Evaluation:

$$\alpha_4 = \gamma_o + \gamma_G + \gamma_{R_i},$$

where

γ_o = occupational exposure,

γ_G = global exposure,

$\gamma_R = \frac{1}{p_o} \sum_i \int_{A_i} p(\vec{x}) \Delta\rho(\vec{x}) d\vec{x}$ = regional exposure,

$\Delta\rho$ = radiation dose due to the energy system of the region investigated,

γ_o and γ_G are independent from the location of the installations.

Attached impacts:
Cancer, genetic effects (also in future years).

5. Land Occupancy Exposure (% of land occupied)

Evaluation:

$$\alpha_5 = \frac{1}{p_o} \sum_i \frac{p_i}{A_i} \Delta A_i,$$

where ΔA_i = area in region i occupied temporarily, p_i = total population of region i.

Attached impacts:
Inaccessibility of land used for mining, power plants, solar energy conversion etc.

Table 3. continued

6. Radioactive waste present (g/cap)

   Attached impacts:
   It has to be guarded, threat of dispersal by sabotage or accidents.

7. Plutonium present (g/cap)

   Attached impacts:
   Similar as for α_6

Table 4. Types of Constraints for Regional Energy Supply Optimization

1. DEMAND CONSTRAINTS:

$\sum_k y_{jk\ell}\, \varepsilon_{k\ell} \geq D_{j\ell}$ $\qquad \varepsilon_{k\ell}$ = Efficiency of Intermediate Energy k in Demand Category ℓ.

2. SUPPLY CONSTRAINTS:

$\sum_k x_{jik}/\eta_{ik} \leq P_{jk}$ $\qquad \eta_{ik}$ = Efficiency of Conversion of Primary Energy i into Intermediate Energy k.

3. BALANCE EQUATIONS FOR INTERMEDIATE ENERGIES:

$\sum_i x_{jik} = \sum_\ell y_{jk\ell}$ for all k

4. CAPACITY CONSTRAINTS:

$x_{jik} \leq \sum_{j'=j-\sigma_{ki}}^{j} \Delta x_{j'ik}$, The Same For Some $y_{jk\ell}$

σ_{ik} = Life Time of Capacities

5. INVESTMENT CONSTRAINTS FOR NEW TECHNOLOGIES:

$\Delta x_{jik} \leq s_{ik} + \Gamma \cdot \sum_{j'=1}^{j-1} \Delta x_{j'ik}$, Γ = Introduction Rate of New Technology

6. CONSTRAINTS FOR INTERCHANGEABILITY OF FUELS:

$y_{jk\ell}\, \varepsilon_{kl} \geq p_{k\ell} D_{j\ell}$, $\qquad p_{k\ell}$ = Minimum Proportion of $D_{j\ell}$ which Has To Be Satisfied With Intermediate Energy k.

Table 4. continued

7. LOAD CONSTRAINTS:

$$\sum_i X_{jik} \le R_n \, \Delta C_{jk} + S_n \, \Delta Q_{jk} \quad , \quad R_n, S_n = \text{const}, \quad n = 1,2,3,$$

$$\Delta C_{jk} = \sum_i \sum_{j'=j-\sigma_{ki}}^{j} \Delta X_{j'ik},$$

ΔQ_{jk} = Total Capacity of off-peak users of Intermediate Energy k.

8. STORAGE BALANCE EQUATIONS:

$$X_{jik} = \varepsilon_{k'\ell} \, \eta_{ik} \, Y_{jk'\ell}$$

9. MISCELLANEOUS CONSTRAINTS FOR COUPLED CONVERSION PROCESSES ETC.

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APPENDIX

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