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MODELING OF THE INFLUENCE OF ENERGY DEVELOPMENT ON DIFFERENT BRANCHES OF THE NATIONAL ECONOMY

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PREFACE

Within the Energy program, this paper contributes to the assessment, comparison, and evaluation of energy strategies, in particular the impact of the energy supply system on other branches of the economy. This impact is characterized by the demand for industrial products necessary for building and operating the energy supply system, the required putting into operation of industrial production capacities, capital investment in the energy supply system and related branches, and the direct and indirect expenses of limited domestic natural resources.

The dynamic model for treating all these characteristics was constructed at the Siberian Power Institute and modified at IIASA.

SUMMARY

In planning future energy supply strategies and evaluating alternatives, the fact that the energy system is embedded in the national economy must be taken into account. This is a general requirement deriving from the system-oriented problem approach. For the elaboration of long-range energy programs, we must make use of tools that help us to answer the following questions:

- How do the requirements of various energy programs differ with respect to the necessary development of other branches of the national economy?

- How much capital, manpower, material, and natural resources would be needed, and when?

- Is a given energy program feasible? If not, what can be done to make it feasible?

Answers to these questions should address both the direct and the indirect requirements of candidate energy programs. Analysis shows that the indirect requirements per unit of energy production capacity are a function of the rate of energy development. The more abrupt the rate increase, the wider the circle of related branches and the higher the indirect material, manpower, and monetary costs. The same effect can be provoked also by increased specific investment in fuel extraction and transportation, rapid transition to new energy sources or new technologies, decreased import of energy equipment and materials, and the like. Therefore, one cannot estimate the indirect expenses in capital, manpower, material, and natural resources without taking the dynamics and actual conditions of energy system development into account.

An interindustrial dynamic model has been elaborated by the author and V. Tkachenko at the Siberian Power Institute for investigating the influence of sizeable long-term changes in the technology, structure, and rate of energy development on other branches of the national economy. The model provides a systematic means of calculating, for any given strategy (variant), the direct and indirect resources required to build and operate the energy supply facilities for providing the fuel mix specified for that variant. Also, the feasibility of various proposed mixes can be assessed in terms of the time, capital, manpower, and materials required for the energy supply system.

In conditional medium- and long-range forecasting, where prices and constraints have maximal uncertainty, the minimum sum of direct and indirect capital investment and other limited resources may be considered an additional criterior for comparing variants. With that aim, it is proposed that our model be used in combination with the Bechtel Corporation

model and the so-called WELMM approach.*

Comparing strategies in terms of this additional criterion is not enough in the case of particularly significant changes in the structure of the energy balance or a large-scale transition to new methods of energy production. In these cases, to confine the comparison to feasible strategies, an iterative step must be introduced. It involves analyzing, to the maximum extent possible, the direct and indirect production relations of energy systems with the national economy. By introducing the constraints on utilization of major resources, the initial goals of the strategies and/or the objective function for optimizing the energy strategies considered are modified.

This approach for a perspective of more than 15-20 years is now being developed at IIASA. It is based on coordination of the Häfele-Manne energy optimization model with a long-term macroeconomic model and with the model described in this paper.

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*See M. Grenon and B. Lapillonne, *The WELMM Approach to Energy Strategies and Options*, Research Memorandum, International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).

Modeling of the Influence of Energy Development on Different Branches of the National Economy

INTRODUCTION

Owing to the high degree of interchangeability of energy resources, the electric power, atomic, oil, oil-refining, gas, and coal industries can be considered as one energy supply system (ESS). Its functioning and development have a close and complex interrelationship with nature, society, and the economy. The investigation and correct registration of these interrelations are indispensable for effective energy policy design.

The so-called production relations, an important part of the entire system of ESS external relations, are considered in this paper. Via these relations, the ESS strongly influences the development of most branches of industry, construction, and transport, as it is a big consumer of their production.* Conversely, insufficient branch development and lack of funds for investment or import of equipment can negatively influence the rates of development of effective energy resources.

Investigating these relations gains in importance because --partly in view of the forthcoming large-scale use of atomic energy and other new energy sources--most countries want to employ their own energy resources and thus rely on their own infrastructure. The final goal of such investigations is to improve the methods of long-term energy policy development by means of more complete registration of the requirements of ESS development variants that the national economy must provide, and of the possibilities for satisfying them.

Work in this direction is being carried out at IIASA in cooperation with the Siberian Power Institute (USSR), the Bechtel Corporation (USA), and other national organizations. The first stage is to design an instrument suitable for approximate quantitative evaluation of the influence of changes in rates, structure, and technology of energy resource production on different branches of the national economy and on total consumption of

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*Thus, for example, in the USSR ESS development requires more than 30% of all industry investment. It consumes, directly or indirectly, 65% of all the tubes manufactured and up to 20% of other metallurgical products, approximately 15-20% of copper and aluminum, 13-16% of cement, and more than 15% of the gross machine-building production [1].

capital investments and other limited resources. Some results of these studies are given in this paper.

EXTERNAL PRODUCTION RELATIONS OF THE ESS

The production, conversion, transport, and distribution of energy resources demand great investments and timely development of the industry branches whose products are involved in the ESS. These branches may then require additional investments and materials, engendering new external production relations of the ESS. These relationships can be presented in a form suitable for analysis if we proceed as follows:

- Choose direct and indirect relations as well as relations connected with supplying products for operational requirements (operational relations) and capital construction (investment relations);
- Represent the formation process of investment relations as a sequence of time-shared events to provide the intended increase in energy resource production;
- Choose conventional time steps and select the related industry branches such that the products at each level can be manufactured simultaneously.

The external production relations of the ESS will thus have a multilevel structure in which the investment relations are presented as vertical and the operational relations as horizontal (Figure 1). The latter have rather complex structures themselves and can be described by input-output matrices.

A given industry branch or enterprise can be placed simultaneously at different time steps and connected with the ESS both directly and indirectly. In the first case, its production is consumed directly by the ESS itself; in the second, it is devoted to development of related branches.

Figure 1 shows that if any level has no increase in production capacity ($\Delta X_p = 0$), all indirect relationships of the ESS are broken, beginning at the next level ($X_{p+1} = 0$, $X_{p+2} = 0, \ldots$). Consequently, the required lead time for developing related branches also decreases.

The development of new capital intensive energy technologies on a large scale necessitates appreciable capital investment in machine building, metallurgy, construction materials, and related industrial sectors. These investments must precede, by five to ten years or more, direct investment in the energy system. This is illustrated by Figure 2, showing the distribution over time of direct and indirect investment

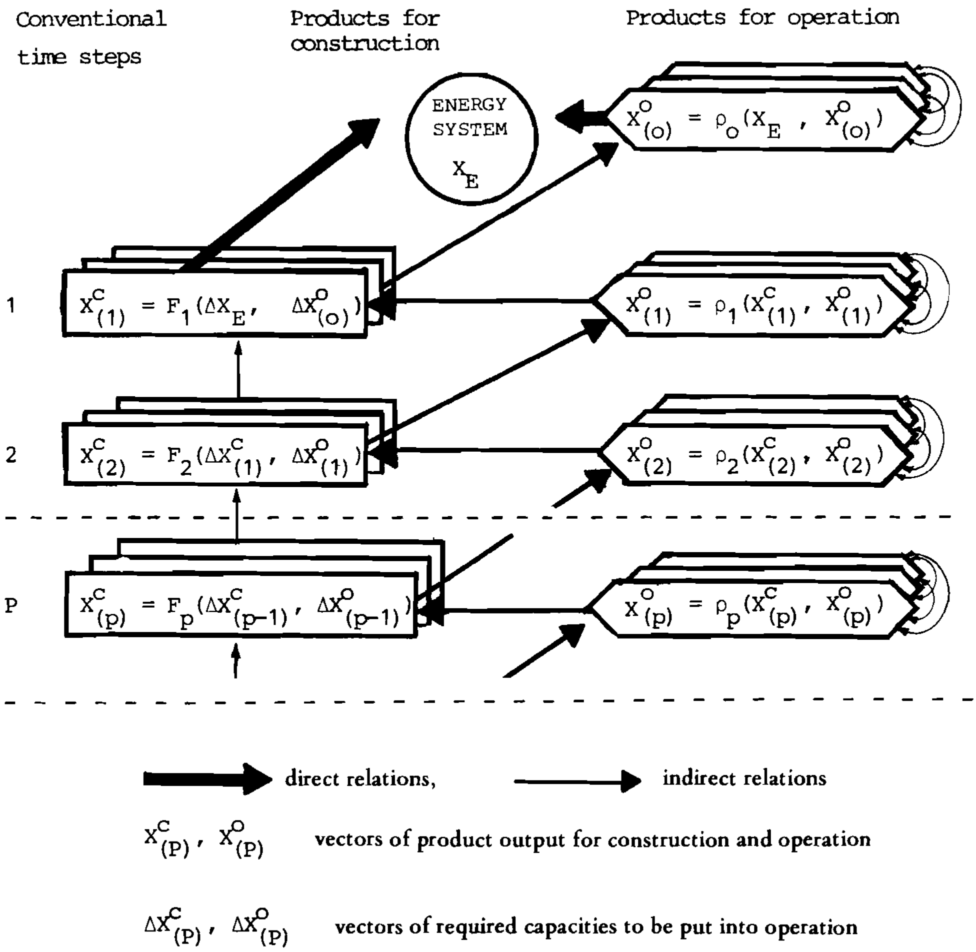

Figure 1. Simplified structure of external production relations of the energy supply system.

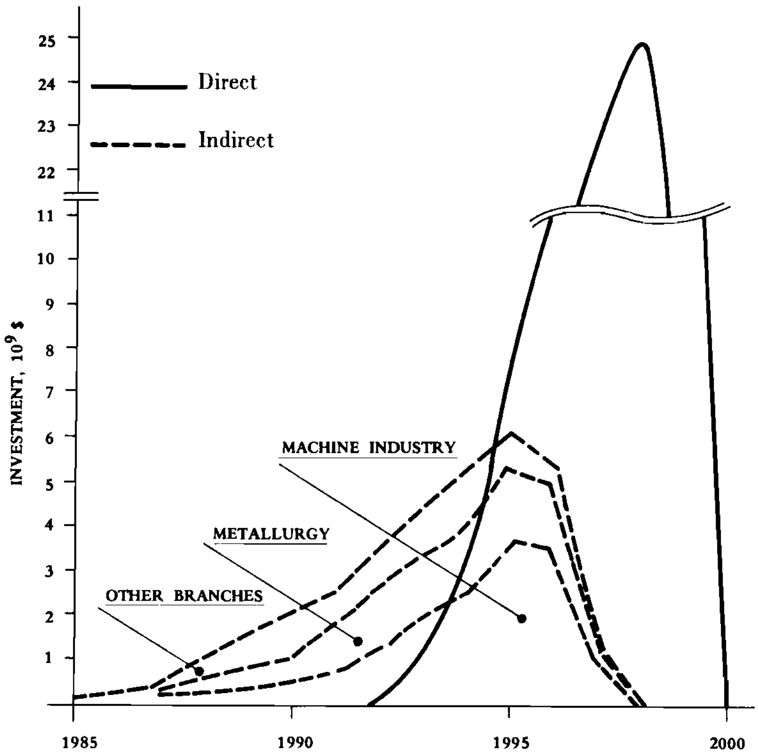

Figure 2. Distribution of direct and indirect investment in FBR development.

for putting into operation fast breeder reactors with 150 TW (e) total capacity during the years 1996-2000.*

Examination of the chain of production relations of the ESS with the branches creating capital reveals that a number of related output levels, and the scales of putting new capacities into operation and production in related branches, are ultimately a function of ESS development rates. When the value of the annual rate of energy resource production does not increase, the investment relations of the ESS are limited by the first related output level and are mainly direct ones. With increasing rates of energy development, the role of the indirect relations also increases. The higher the planned rates, the wider the

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*Some Bechtel Corporation data were used for these calculations. The constuction period is taken to be three years for all facilities.

circle of related branches, the greater the expenses for investment, labor, and material resources, and the longer the time for their development.

This is confirmed by the results of calculation (Figures 3-6) made with the help of the model described below. Here the oil and gas deposits of western Siberia and the Kansko-Achinskii coal fields have been taken into consideration. Specific investments in fuel extraction and transportation to the European part of the USSR have been taken as invariable in all versions.

Obviously, an increase in indirect expenses per unit of energy production capacity may be due to factors other than increasing development rates, for example increased specific investments (material expenses) in fuel extraction and transportation, transition to new energy sources or technologies, decreased import of equipment or materials for energy facilities, etc. In reality, all these factors can play a role in different combinations. Moreover, indirect production relations of a peculiar type can arise when industrial and agricultural production for export must be increased to compensate the expense of energy resource import.

All this testifies to the fact that the quantitative evaluation of the influence of ESS development on other branches of the national economy through the system of direct and indirect production relations is a complex task that demands an adequate instrument.

ECONOMIC-MATHEMATICAL MODEL

The problem of defining the influence of energy development variants on various branches of the national economy can be reduced to the quantitative estimation of the following characteristics:

- Required output of, or direct and indirect expenses for, different types of industrial products and services for the energy development variant considered;
- The required putting into operation of production capacities in related branches of industry;
- The time needed to put those capacities into operation;
- Capital investment in the ESS and related branches;
- Direct and indirect expenses of limited resources (manpower, materials, natural resources, etc.)

Naturally, the model for determination of these characteristics must be multibranch and dynamic. It must also take into account construction lags (the gap in time between the beginning

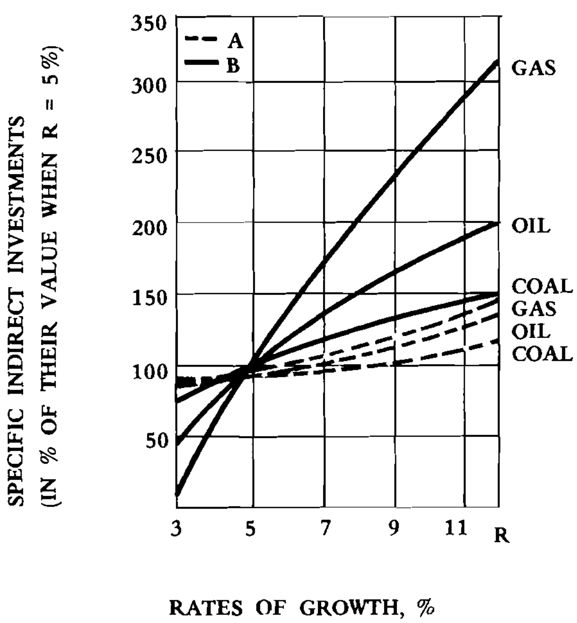

Figure 3. Dependence of indirect capital investment on growth rates of fuel mining.

A – Growth rates identical before and during development period

B – Growth rates variable (R = 5% before development period).

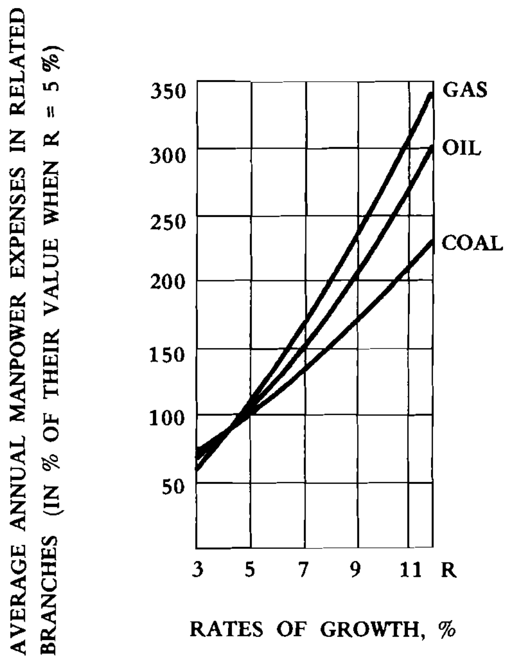

Figure 4. Dependence of indirect manpower expenses on the growth rates of fuel mining.

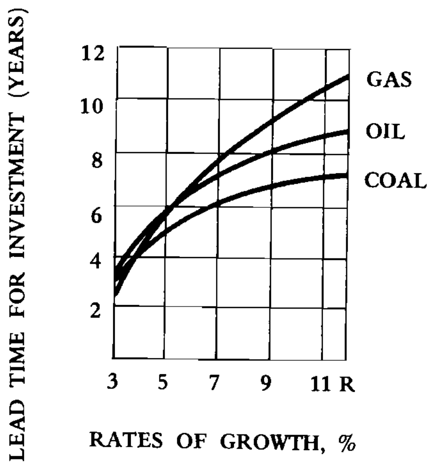

Figure 5. Required lead time for indirect investment.

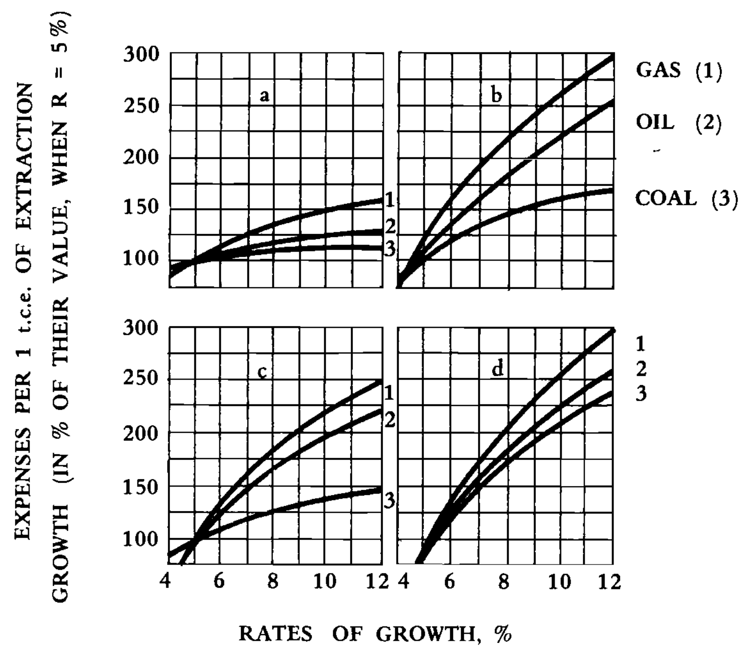

Figure 6. Effect of changing rates of gas, oil, and coal extraction on specific expenses.

a – cement, b – construction machinery,
c – machine tools, d – metallurgical equipment.

of investment and putting the objects into operation) and equipment and material consumption during the years of construction; must describe the interbranch relations, mainly in physical terms; and must be convenient for computing.

Only a few of the existing interbranch models meet these requirements; and even those are not well adapted for evaluating the external production relations of the ESS, as they are designed for the determination (planning) of interbranch balance and fail to take into account some peculiarities of the problem considered (Table 1). The model described here was developed to meet all the requirements outlined and take account of the peculiarities.*

The initial data for our model are the volumes and methods of production, conversion, and transportation of individual energy resources and other indicators characterizing given variants (strategies) of prospective energy development. All the data must be given for each year of the period considered. This period must include not only the years of the energy development as such, which will differ from one variant to another, but also a number of preceding years. Only then is it possible to define correctly the predicted development of related branches that is necessary.

These branches and the nomenclature of industrial output taken into account in the model depend on the perspective and the accuracy of estimation. In particular, for the development variants of the USSR ESS during 1976-1990, the related branches were represented in the model by the following aggregated types of production:

Iron and steel industry	- 10
Nonferrous metallurgy	- 6
Construction materials	- 6
Chemical industry	- 2
Machine building	- 34

Two types of construction and three types of transport means were also distinguished.

For the related branches chosen for compilation of the model, the following assumptions were made:

- Products are manufactured by a single method--that is, there is no choice of technology or distribution in the model: the most progressive production methods for the variant considered are assumed;

- The coefficients (standards) of material, monetary, and manpower expenses per unit of production or capacity do not depend on the production scales.

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*Model modifications are described in [1,2,3].

Table 1. The tasks of evaluating the ESS production relations and of interbranch balance planning.

Characteristics to be compared	Evaluation of external relations	Interbranch balance planning
Aims of calculations	To define possible reactions in the national economy according to the changes in technology, structure, or rate of energy development	Input-output balance
Initial data:		
Exogenous variables	Value and methods of production and transportation of different energy resources	Final production consumption of all branches
Technical-economic indices	For the new enterprises of a limited number of branches	Average data for all branches
Conditions and requirements:		
Character of production growth	Any type	Not decreasing
Start of development of non-energy branches	Unknown; being searched in the process of calculation	Given
Production capacities at the beginning of the period considered	Unknown in some branches	Known
Registration of development beyond the period considered	Not obligatory	Obligatory

These assumptions are typical for interindustry balance models. The indices of production and putting into operation of production capacities are interrelated: the growth of demand for a given type of product is one of the main factors in enlarging industrial capacities, which in their turn provoke additional demand for industrial products. It is known that the satisfaction of demand must be timely and might cause increased capacities in other branches of industry. This interrelation is reflected in the model by two types of equations.

Equations of the first type describe, for each production type i and each year t, the balance of output and consumption for the operational needs and capital construction started, continued, and completed during that year:

$$X_{i(t)} = \sum_{j=1}^{n} \alpha_{ij} X_{j(t)} + \sum_{j=1}^{n} f_{ij}^{t,t} N_{j(t)} + \sum_{j=1}^{n} f_{ij}^{t,t+1} N_{j(t+1)}$$

$$+ \ldots + \sum_{j=1}^{n} f_{ij}^{t,t+\ell} N_{j(t+\ell)} + Y_{i(t)} - y_{i(t)}$$

$$(i,j = 1,2,\ldots,\eta;\ t = t_o, t_o+1, \ldots, T)$$

where $X_{i(t)}$ = volume of production i in year t;

$N_{j(t)}$ = putting into operation of capacities in branch j in year t;

$Y_{i(t)}$ = guaranteed demand for production i (direct expenses for development of the ESS);

$y_{i(t)}$ = import of production i;

a_{ij} = current expenses of production i for manufacturing of product j;

$f_{ij}^{t,\tau}$ = expenses of production i in year t per unit of capacity increase j put into operation in year τ $(\tau = t,\ t+1, \ldots, t+\ell_j)$;

ℓ_j = construction lag in the branch j.

Equations of the second type determine the value and conditions of putting the new production capacities into operation. These equations may be written in several ways. The simplest is based on describing the capacities additionally required by the end of year t as the difference in estimated production volumes in the next and the current year (in the model, the nonnegativeness of this difference must be checked):

$$N_{i(t)} = \begin{cases} X_{i(t+1)} - X_{i(t)}, & \text{if } X_{i(t+1)} > X_{i(t)} \\ 0 \quad , & \text{if } X_{i(t+1)} \leq X_{i(t)} \end{cases}$$

$$= \max \left(X_{i(t+1)} - X_{i(t)};\ \ 0\right)$$

$$(i = 1,2,\ldots,n;\ t = t_o,t_o+1,\ldots,T)$$

The required capital investments for developing a certain branch in year t are determined as an amount of money needed for completing the construction objects started earlier and for beginning and continuing construction of new production capacities to be put into operation during the following years.

The model is a block-structure type (Table 2). The first block serves as an estimator of direct expenses of different types of production, investments, labor, and other resources needed for realization of a given strategy of ESS development. The investments in construction of a non-productive infrastructure for the undeveloped areas of new energy facilities must be included. The results of these estimations serve as initial (input) information for the second block, where the minimum required production in related branches (minimum total expenses) for a given development variant of the ESS is determined. It is assumed that direct and indirect energy production requirements will be satisfied without putting into operation production capacities in related branches.* An exception is made only for related enterprises, whose production is consumed mainly by the ESS: energy equipment, mining and drilling equipment, and so forth. In this case, the number of related branches is minimal, whereas the total expenses of any one product connected with realization of the variant considered are composed of the cost of development of the complex itself, creation of the infrastructure, increase of production capacities in some related branches, and current production consumption of all branches related to the ESS.

In the third block the limitations on putting the capacities of related branches into operation are removed. The model estimates the need for additional increases in production in general machine building, metallurgy, construction materials, and some other branches. It also determines additional capital, manpower, and material requirements.

The sum of the results of second- and third-block calculations gives the maximum value of both the output of related branches and the total direct and indirect expenses of capital, manpower, and limited resources for ESS development.

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*Even where the estimation indicates that such capacities must be created, the expenses for them are not taken into account.

Table 2. EXTERNAL PRODUCTION RELATIONS OF THE ENERGY SUPPLY SYSTEM

Equation number	Variable Sought	Model Equations	Notations of Indices and Assigned Parameters
	First Block		
1	Input of capacities in ESS: $N_{k(t)}$	$N_{k(t)}=\max(\bar{X}_{k(t+1)}-\bar{X}_{k(t)};0)$	k = index of energy resources and supply facilities ($k\epsilon K$)
2	Capital investment in extraction, conversion and transportation of energy resources: $I_{k(t)}$	$I_{k(t)}=\sum_{t=\tau}^{t+L_k} s_k^{t\tau} c_k N_{k(\tau)}$	i,j = indices of related branches and enterprises ($i,j\epsilon n$) p = index of equipment for ESS (p Pcn)
3	Direct material and equipment expenditure for ESS: $\bar{X}_{i(t)}$	$\bar{X}_{i(t)}=\sum_{k\epsilon K} A_{ik}\bar{X}_{k(t)}+\sum_{k\epsilon K}\bar{A}_{ik}I_{k(t)}+$ $+\sum_{k\epsilon K}\sum_{\tau=t}^{t+L_k} s_k^{t\tau} f_{ik} N_{k(\tau)}$	m = index of construction machinery ($m\epsilon Mcn$) t = index of the year under consideration ($t=t_o,t_{o+1},\ldots,T$)
4	Output of construction machinery for ESS: $\bar{X}_{m(t)}$	$\bar{X}_{m(t)}=\max[\sum_{k\epsilon K}\bar{A}_{mk}(I_{k(t+1)}-I_{k(t)});0]$	τ = index of the year of capacity input
5	Manpower for ESS operation and construction: $L_{k(t)}$	$L_{k(t)}=l_k^o\bar{X}_{k(t)}+l_k^c I_{k(t)}$	$\bar{X}_{k(t)}$ = output of ESS products in year t
6	Investment in unproductive infrastructure: $I_{u(t)}$	$I_{u(t)}=\max[\sum_{k\epsilon K}\sum_{\tau=t}^{t+L} u_{s_u}^{t\tau} c_u \delta \times$ $\times (L_{k(\tau+1)}-L_{k(\tau)});0]$	c = capital investment per unit of capacity $s^{t\tau}$ = coefficient of investment, material and equipment distribution by construction year
	Second Block		
7	Input of capacities for output of special energy equipment: $N_{p(t)}$	$N_{p(t)}=\max(\bar{X}_{p(t+1)}-\bar{X}_{p(t)};0)$	L = duration of construction period
8	Investment in development of energy equipment: $I_{p(t)}$	$I_{p(t)}=\sum_{\tau=t}^{t+L} {}^{p}s_p^{t\tau} c_p N_{p(t)}$	A_{ij} = current expenditure of production i on production of unit j

9	Output of construction machinery for enterprises producing energy equipment: $\tilde{X}_{m(t)}$	$\tilde{X}_{M(t)}=\max[\sum_{p\epsilon P}\bar{A}_{mp}(I_{p(t+1)}-I_{p(t)});0]$	$\bar{A}_{ij}$ = material and equipment expenditure per unit of investment
10	Minimum necessary output of related branch products: $\tilde{X}_{i(t)}$	$\tilde{X}_{i(t)}=\sum_{j\epsilon n}A_{ij}\tilde{X}_{j(t)}+\sum_{p}\bar{A}_{ip}I_{p(t)}+$ $+\sum_{m\epsilon M}A_{im}(\bar{X}_{m(t)}+\tilde{X}_{m(t)})+\bar{A}_{iu}I_{u(t)}+$ $+\bar{X}_{i(t)}-Y_{i(t)}$	f_{ij} = expenditure for energy equipment per unit of capacity $1^{o},1^{c}$ = coefficients of manpower expenditure for operation and construction
11	Minimum necessary volume of manpower in related branches: $\tilde{L}_{i(t)}$	$\tilde{L}_{i(t)}=\sum_{i\epsilon n}1_{i}^{o}\tilde{X}_{i(t)}+\sum_{p\epsilon P}1_{p}^{c}I_{p(t)}-$	δ = family coefficient $Y_{i(t)}$ = import of product i in year t
	<u>Third Block</u>		
12	Input of capacities in related branches excluding energy equipment: $N_{i(t)}$	$N_{i(t)}=\max(X_{i(t+1)}-X_{i(t)};0)$	
13	Investment in development of related branches: $I_{i(t)}$	$I_{i(t)}=\sum_{t=\tau}^{t+L_i}S_{i}^{t\tau}c_{i}N_{i(\tau)}$	
14	Output of construction machinery for related branches: $I_{i(t)}$	$X_{m(t)}=\max[\sum_{i\epsilon n}\bar{A}_{mi}(I_{i(t+1)}-I_{i(t)});0]$	
15	Additional output of related branch products: $\Delta X_{i(t)}$	$\Delta X_{i(t)}=\sum_{j\epsilon n}A_{ij}\Delta X_{j}+\sum_{j\epsilon n}\bar{A}_{ij}I_{i(t)}+$ $+\sum_{m\epsilon M}A_{im}X_{m(t)}$	
16	Maximum output (maximal total expenditure) of related branch products: $X_{i(t)}$	$X_{i(t)}=\tilde{X}_{i(t)}+\Delta X_{i(t)}$	
17	Maximum manpower expenditure for related branch development: $L_{i(t)}$	$L_{i(t)}=\tilde{L}_{i(t)}+\sum_{i\epsilon n}1_{i}^{o}\Delta X_{i(t)}+\sum_{i\ n}1_{i}^{c}I_{i(t)}$	

For the calculations, an iterative algorithm has been worked out that provides problem solutions in five to eight iterations.

POSSIBLE AREA OF MODEL IMPLEMENTATION

The model described should be considered, first of all, as an instrument for investigating the influence of large and long-term changes in technology, structure, and rate of energy development on other branches of the national economy. The results of such investigations are important for estimation and comparison of different strategies and for elaboration of an effective long-term energy policy. In particular, with the model we can obtain additional criteria for comparing and evaluating possible indirect consequences of realization of a given strategy. These criteria may include: 1) minimum total direct and indirect investment, manpower, limited material and natural resources; and 2) ease (reliability) of strategy realization.

As a rule, the second criterion does not contradict but supplements the first. The wider the circle of related branches is, the earlier should their development begin; and the more limited resources are required for development, the more difficult it is to realize a given strategy. Moreover, the probability of errors in evaluating the real effectiveness of a strategy is higher. Therefore, when other conditions are equal, the strategy involving fewer demands on related branch development and less expense for limited resources deserves preference.

The necessity for such additional criteria increases with the uncertainty in the cost indices and constraints used in optimizing the ESS. Comparison of the results of optimization in terms of these criteria is not enough in the case of significant changes in the structure of the energy balance and a large-scale transition to new methods of energy production. In the process of optimization itself, the direct and indirect production relations of the ESS with other branches of the national economy must be taken into account to the maximum extent possible, by means of correcting the objective function and/or introducing the constraints on utilization of limited resources.

Such an approach for a perspective of more than 15 to 20 years is being developed at IIASA. It is based on coordination of the Häfele-Manne optimization energy model [4] with a long-term macroeconomic model [5] and with the model described in this paper.

Among other possible uses of the model we may mention the development of individual energy programs, i.e. determination of the actions and time needed to achieve a given aim (for instance, developing fission or fusion on a large scale). Moreover, the model allows us to analyze different variants of import of equipment and materials for the ESS and to evaluate the economies of capital investments and other expenses for related branch development. The model can also be implemented for rough estimation of changes in related branch development when plans or programs are modified during realization.

In conclusion, it should be said that all the tasks mentioned make their own demands on the structure of the model, the ways in which it is used, the completeness and quality of the initial data, and the composition of the related branches and products considered.

Acknowledgment

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