Control
and Cybernetics
VOL. 6 (1977) No. 3–4

Optimal investment strategy of resource-energy system
Part 1. The statement of the problem

by

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The optimal investment strategy problem of the resource-energy consumer system, when the costs are dependent upon time and investment intensity, has been stated in Part 1. The method of solution to this problem will be proposed in Part 2. The coal-nuclear and nuclear subsystems will be investigated among all the possible subsystems of the resource-energy consumer system. The first constitutes the transition from coal fired technologies to coal conversion technologies by use of the nuclear energy. The second is the transition from the present reactor generation with U-235 fuel cycle to the self-sustaining reactor generation which will enable us to use U-238 and Th-232 in a more efficient way.

Introduction

The rising need for energy is confronted with a number of new problems [1–7]. They are the exhausion of mineral oil and natural gas, a mounting desire to preserve our environment and the last increase of the oil and gas prices. The step being taken up by industrial countries is the increased support for research and development of the substitution for oil and gas by the utilization of high temperature reactors, and to make it possible to extract more energy from a given amount of nuclear fuels by the utilization of breeder reactors [9–11].

The development of the high temperature gas cooled reactors, HTGR, brings the possibility of the utilization of energy as a heat to processing operations. It will enable to produce the substitutions for oil and gas from coal. By use of the cheap thermal energy from HTGRs the production of hydrogen by the water splitting or as a result of steam-coal reaction becomes possible [12–16].

The breeder reactors will enable not only to use the nuclear fuel in the more economical way but also to make the lowgrade ore to be usefull.

In the future the nuclear energy will integrate the industrial sectors with the energy sector [17–19]. It is due to:

— the size of nuclear units which is dictated by the economic reasons,

— the cascade form of the utilization of nuclear heat because of different temperature ranges when applied to different processes,

— the breeders which will produce fissible materials for HTGR and will partly satisfy the electrical energy demand.

Bearing in minde the above the expantion planning over the few decades time horizon should involve the integrated resource-energy consumer system. The global objective should be:

— the selection of the conversion technologies, and

— the time distribution of introducing these technologies to the resource-energy system,

on the transition paths of primary energy carriers from the energy resources to the energy consumers such that the costs of energy consumer products will take minimum when a number of constraints are satisfied.

Previous attempts

Hoffman and Cherniavsky considered energy resources allocation to fifteen demand sectors [20–22]. Hafele and Manne investigated an optimal strategy on a transition from fossil to nuclear fuel.

The optimization formalisms applied in both cases does not permit to relate costs and investment revenue which are time dependent. On the other hand, the costs of a number of processes are functions of production level, which is in turn determined by the investment revenue.

The scope of this paper

The problem of optimal investment strategy of resource-energy system is presented in two Parts.

The scope of Part 1 is to state the optimal investment strategy problem of the resource-energy consumer system when the costs are dependent upon time and investment intensity.

It will involve the formulation of the general planning problem, the decomposition of the planning organization to allocate the different planning functions in the general problem, the formulation of the expansion planning in the continuous form and the presentation of the economic model to be used and the set of constraints to be imposed upon the optimization problem.

The scope of Part 2 will be to propose the method of solution to this problem. The optimal investment strategy problem will be decomposed into smaller subsystems by use of the gradient iteration procedure. This procedure has been given by Sanders [23] and has been generalized by Kulikowski [24] for the case of functionals in Banach space. Each subsystem will involve the bunale of transition paths with the origin in the appropriate resource sector. The local problems with nonquality operator constraints will be solved by means of the functional Lagrange method given by Kulikowski [24, 25].

Structure of the resource-energy consumer system

It is assumed that the transition from the primary energy carrier resources to the energy consumers involves four successive steps. They are identified with the following systems:

— energy carrier resource extraction system called the resource system,

— transport system of the primary energy carriers called the transport system,

— conversion system of the primary to the secondary energy carriers called the conversion system,

— nonelectrical energy consumer system.

Each of the systems consists of branch sectors and can be divided into territorial regions.

The primary energy carriers can be converted into nonelectrical or electrical forms of the secondary carriers. Therefore we will distinguish between nonelectrical and electrical energy sectors of the conversion system.

The terminals of the general resource-energy system are the sectors of the nonelectrical energy consumer system and the electrical energy sectors of the conversion system.

The following notation will be used: w, v, x — sector sets of the resource, transport and nonelectrical energy consumer systems, respectively; y, z — sector sets of the electrical and nonelectrical energy sectors of the conversion system, respectively, (small letters will be used to denote production in production units, whereas capital letters will be reserved for production in the equivalent monetary units); n, l, i — indices of the resource, transport and nonelectrical energy consumer sectors, respectively; j, k — indices of the electrical and nonelectrical energy sectors of the conversion system, respectively; h — index of the territorial region (when the mean value of the national production is considered, this index will be omitted).

The set of the resource system may consist of the coal, lignite, natural gas, oil, uranium 238 and thorium 232 sectors.

The elements of the transport system may be railway, pipeline and water transport sectors.

The electrical energy sectors of the conversion system, acceptable from the technical progress point of view, can involve: coal-fired power plants; gas-fired power plants when partial combustion of the coal is employed to supply energy for the endothermic gasification reaction; nuclear power plants.

The nonelectrical energy sectors of the conversion system can involve the following technologies: coal gasification when partial combustion of the coal is employed to supply energy for the endothermic gasification reaction; coal gasification and liquefraction when high temperature heat is used to supply energy for the endothermic gasification reaction; hydrogen production as a result of the steam and coal reaction when high temperature heat from nuclear source is used; hydrogen production by means of the termochemical water-splitting method.

To the set of the primary and secondary energy carrier consumer sectors belong among others the petrochemical, chemical and steel-making industry as well as the municipal-residential heating.

The possible transition paths from the energy carrier resources to the terminal sectors are represented on Fig. 1.

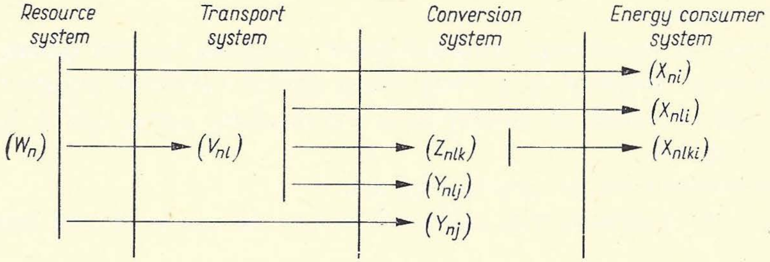

Fig. 1. The possible transition paths from the primary energy carrier resources to the terminals of these transitions

The general planning problem

To formulate the problem of the optimal option of the transition paths it is assumed that the production capacities x_i and y_j of every nonelectrical energy sector and electrical energy sector, respectively, are the subsets of the elements x_{ipm}, y_{jrm}, that is

$$x_{ipm} \in x_i \in x=(x_i),\ y_{jrm} \in y_j \in y=(y_j),$$

where: x_{ipm} — maximum production capacity of a unit belonging to the i-th nonelectrical energy consumer sector, where p denotes the type of unit and m the year of its commissioning, y_{jrm} — maximum production capacity of a unit belonging to the j-th electrical energy sector, where r denotes the type of unit and m the year of its commissioning, $\bar{x}_{ipm}$, $\bar{y}_{jrm}$ — production outputs associated with units of type p and r, respectively, installed in the m-th year, $\bar{I}_{ipm}$, $\bar{J}_{jrm}$ — discounted investment expenditures per unit of capacity associated with units of type p and r, respectively, installed in the m-th year, c_{ipm}, c_{jrm} — operating costs per unit of capacity associated with units of type p and r, respectively, installed in the m-th year.

For the purpose of the general statement of the problem we will extend the electrical energy investment problem, given by Anderson [26], when to demands involve also the nonelectrical energy.

PROBLEM A. Given:

1) time interval $[0, T]$ determined by planning horizon T;

2) nonelectrical energy demand, realized by nonelectrical energy sectors of the conversion system, $N_i(t)$, in heat quantity units, $t \in [0, T]$, $i = 1, 2, \ldots, I$;

3) electrical energy demand, realized by electrical sectors of the conversion system, $E(t)$;

4) sets of units x_{ip}, y_{jr}, available in the time interval $[0, T]$, $i = 1, 2, \ldots, I$, $p = 1, 2, \ldots, P$, $j = 1, 2, \ldots, J$, $r = 1, 2, \ldots, R$;

5) $\bar{I}_{ipm}, \bar{J}_{jrm}, c_{ipm}, c_{jrm}$ — discounted capital and operating costs per unit capacity associated with units of type p and r of the i-th nonelectrical and j-th electrical energy sectors, respectively, installed in the m-th year, $m = 1, 2, \ldots, M$, $M = T/\Delta t_y$ $(\Delta t_y = I$ year).

Find:

— type and size of the considered units;

— time schedule of purchasing new units in the successive years of the time interval $[0, T]$ (to satisfy the nonelectric and electric energy demands);

such that the total production costs of the terminal sectors represented by the objective function

$$Q = \sum_i \sum_m \sum_{p \in P} \bar{I}_{ipm} x_{ipm} + \sum_i \sum_m \sum_{p \in P} \sum_s c^s_{ipm} \bar{x}^s_{ipm} \cdot \Delta t_s + \\ + \sum_j \sum_m \sum_{r \in R} \bar{J}_{jrm} y_{jrm} + \sum_j \sum_m \sum_{r \in R} \sum_s c^s_{jrm} \bar{y}^s_{jrm} \cdot \Delta t_s \quad (1)$$

will be minimum when the appropriate constraints acting in different time scale (within the one day and one year time periods as well as within the overall time interval $[0, T]$) are satisfied, where: Δt_s — the time subinterval of the interval $[0, T]$.

Equation (1) represents the global objective function of the total planning problem which consists of the few several planning functions. We will decompose the planning organization in general on the basis of the objective function given by eq. (1). It will be done in order to emphasize the relations between the planning functions in various time ranges. It is of particular importance when the resource-energy system comprises as elements nuclear reactors. Because of the long term nature of the nuclear fuel cost, the fuel management scheme and the unit operation, the coordination of the planning executed on various time scales, is disirable.

Decomposition of the planning organization [27, 28]

The decomposition of the planning organization is performed with respect to the planning functions which are realized on various time scales. They form a hierarchy of planning activities. The conditions which should be satisfied by the decomposed system are the following:

1) the information sets available to each level of planning are distinct subsets of the total information set, that is

$$y_n = A_n\, y \tag{2}$$

where: A_n is a matrix with zero and unit elements;

2) the input signals identified on each level are discrets;

3) the average sampling period of the output on the n-th level, T_n satisfies the following ordering:

$$T_{n-1} \ll T_n \ll T_{n-1}. \tag{3}$$

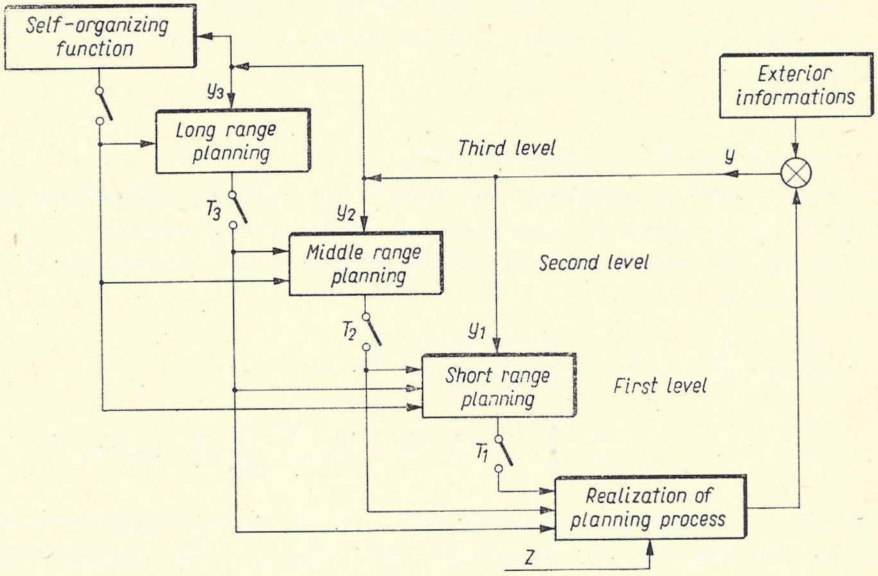

Fig. 2. Hierarchical structure of the decomposition of the planning

Figure 2 shows the structure of the decomposition of the planning. Z denotes the perturbations encountered by utility systems. The elements of the perturbation set, Z, are: extended forced outages; delay of unit instalations; changes in interchange agreements; fuel curtailments, which are of random nature. They are the cause that the actual operating conditions of the utility system differs from the forcasted conditions. If this difference is significant, a revised forecast must be prepared to evaluate the future operating requirements of the system.

In our considerations we will not take into account the above mentioned perturbations. We assume that the highest level of the organization decomposition structure is assigned as a feed-back action to compensate the perturbations by intervening in the short, middle and long range planning levels.

In order to determined the functions to be satisfied on the seperate levels let us write the objective functions (eq. (1)) in the form

$$Q = Q^x + Q^y, \tag{4}$$

where:

$$Q^x = \sum_i \sum_m \sum_{p \in P} \bar{I}_{ipm} x_{ipm} + \sum_i \sum_m \Delta Q^x_{im}, \tag{5}$$

$$Q^y = \sum_j \sum_m \sum_{r \in R} \bar{J}_{jrm} y_{jrm} + \sum_j \sum_m \Delta Q^y_{jm}, \tag{6}$$

$$\Delta Q^x_{im} = \sum_p \Delta Q^x_{ipm}, \tag{7}$$

$$\Delta Q^y_{jm} = \sum_r \Delta Q^y_{jrm}, \tag{8}$$

$$\Delta Q^x_{ipm} = \sum_s c^s_{ipm} \bar{x}^s_{ipm} \cdot \Delta t_s, \tag{9}$$

$$\Delta Q^y_{jrm} = \sum_s c^s_{jrm} \bar{y}^s_{jrm} \cdot \Delta t_s. \tag{10}$$

Equations (9), (10) determine the function of the short-range planning level. It involves the daily or weekly economic dispatch of units, start-up and shut-down of generating units, subject to the energy demand constraints. The second level incorporates the middle range planning. According to eqs. (7), (8) it concerns questions which refer problems as scheduling for utilization nuclear, hydro and fossil units, scheduling nuclear refueling and scheduling maintenance outages within multi-year time period, subject to system reliability constraints and energy demand constraints. The long-range planning level, subject to the energy demand constraints within the time period $[0, T]$, is concerned with questions related to type, size and timing of capacity additions, fuel requirements and refirement of older units, according to eqs. (4) (5) (6).

Expansion planning

The fourth level will be introduced to the decomposition structure of planning organization. The objective of this level is to choose for each *i*-th nonelectrical energy consumer sector and *j*-th electrical energy sector the transition paths from appropriate sector of resource system through the sectors of transport and conversion system to these *i*-th and those *j*-th sectors over the planning horizon *T*, and the timing of these transition paths such that the objective function

$$Q = Q^x_i + Q^y_j \tag{11}$$

will be minimized, where: Q^x_i is the local objective function of the *i*-th nonelectrical energy consumer, Q^y_j is the local objective function of the *j*-th electrical energy sector.

The objective function of the third level, instead of eqs. (5) (6), will be expressed by

$$\Delta Q^x_i = \sum_m \sum_{p \in P} \bar{I}_{ipm} x_{ipm} + \sum_m \Delta Q^x_{im}, \tag{12}$$

$$\Delta Q^y_j = \sum_m \sum_{r \in R} \bar{J}_{jrm} y_{jrm} + \sum_m \Delta Q^y_{jm}. \tag{13}$$

The primary role of this level is to allocate the technology capacities of the transitions from resources to terminals on the fourth level chosen, among types and sizes of separate units within separate sectors. The objective of the second and first levels remain unchanged.

The expansion planning will be considered in the continuous form in the sense of the averaged investment expenditures over each sector of the overall system. Assuming that

$$\bar{x}_{ipm} \to x_{ipm},\ \bar{y}_{jrm} \to y_{jrm} \text{ when } t \to 0 \tag{14}$$

and taking into account the relations

$$\bar{I} = I\,\Delta t,\ \bar{J} = J\,\Delta t, \tag{15}$$

where: I, J are investment intensities of nonelectrical energy consumer and electrical energy sectors, respectively, the objective function (eq. (1)) will be of the form

$$Q = \sum_i \sum_{p \in P} \left\{ \int_0^T I_{ip}(t)\, x_{ip}(t)\, dt + \int_0^T c_{ip}(t)\, x_{ip}(t)\, dt \right\} + \\ + \sum_j \sum_{r \in R} \left\{ \int_0^T J_{jr}(t)\, y_{jr}(t)\, dt + \int_0^T c_{jr}(t)\, y_{jr}(t)\, dt \right\}. \tag{16}$$

After averaging over p and r types and bearing in mind that the total cost is the sum of discounted capital and operating costs over the planning horizon T, we will get

$$Q = \sum_i \int_0^T c_i(t)\, x_i(t)\, dt + \sum_j \int_0^T c_j(t)\, y_j(t)\, dt \tag{17}$$

or

$$Q = \sum_i \int_0^T X_i(t)\, dt + \sum_j \int_0^T Y_j(t)\, dt \tag{18}$$

where: X_i, Y_j are the production intensities of the i-th nonelectrical energy consumer sector and the j-th electrical energy sector in monetary units per time unit, respectively.

Economic model [24, 29]

The growth model of Harrod—Domar will be applied. It is determined by:
1) production intensity condition

$$Y = C + I; \tag{19}$$

2) financial resource condition

$$I = v \frac{dY}{dt} \tag{20}$$

by assumption that $v = \frac{F}{G} = \text{const.}$;

3) full employment condition

$$L=uY; \tag{21}$$

where: Y, C, I — production, consumption and investment intensities, respectively, in monetary units per time unit, v — absorptive capital of production, F — desired investment expenditure, G — production growth, L — employment, u — constant coefficient which determines the labour demand.

Assuming that:

1) production equals demand,

2) consumption is described by the following production function $C=cY=cY$, we will get for the multisector cooperative economic model, in which the exchange of production between separate sectors exists, the following relationships from:

— production intensity condition

$$a_{ii}\, Y_i(t)=\sum_{j\neq i} b_{ij}\, Y_j(t)+\sum_{j} c_{ij}\, I_{ij}(t)+d_i(t); \tag{22}$$

— financial resource condition

$$Y_i(t)=Y_i(0)-\frac{1}{v_i}\sum_{j}\int_{0}^{T} I_{ij}(\tau)\, d\tau \tag{23}$$

where: i, j — sector indices, j — cooperative sector index, $Y(0)$ — initial value of production intensity, a, b, c — given nonnegative numbers.

The term on the left hand size of eq. (22) represents the production intensity worth Y_i decreased by that fraction of production intensity worth $b_{ij}\, Y_i$, which is utilized by the i-th sector itself for operating costs. The successive terms on the right hand side of eq. (22) represent, respectively: 1 — sum of these fractions of production intensity worth of the i-th sector, which are sold to the j-th cooperative sectors, 2 — sum of these fractions of production intensity worth of the i-th sector which are allocated to the investment purpose of the i-th sector itself and the cooperative sectors, 3 — the fraction of the i-th sector production intensity worth which is delivered to external needs.

Equations. (22), (23) will be utilized by the following assumption:

1. The only investors on the transition paths from the primary carrier resources to the energy consumers are the terminals of the overall resource-energy system, that is the nonelectrical energy consumer sectors and the electrical energy sectors of the conversion system.

2. The brutto production worth of each sector investor must provide for the recovery of discounted investment and operating expenses.

3. The brutto production worth of the remaining sectors is balanced by summed up production worth which is sold to cooperative sectors.

4. The electrical energy demand of the national economy is expressed by $E(t)$, $t \in [0, T]$. The electrical energy demand of the seperate sectors can be treated as a cooperative exchange between sectors.

5. The transmission losses of energy are ignored, or it is assumed that they can be aggregated appropriately with the generating costs of particular sectors.

6. The attainability of the given technology which is a result of the technical progress within the planning time period T, is determined by the time lag and inertia of the realization of the investment expenditures.

7. The unit discounted production costs are determined by the relation

$$c[I(t)]=a(t)+b[I(t)]. \tag{24}$$

8. In general the discounting on the discrete present worth of the discounting factor is of the form

$$F=(1+i)^{-n} \tag{25}$$

in which n is the number of time periods from the present date to the time at which payment is made, and i is the discounting factor. It is possible to modify relationship (25) for continuous discounting. The approach used [30] is to imagine a limit process by the length of a time period becomes smaller and smaller but remains discrete. For this case we have

$$F=e^{-gt} \tag{26}$$

where

$$g=\ln(1+i) \tag{27}$$

which means that the present P worth of a payment R is defined as

$$P=Re^{-gt}. \tag{28}$$

Such approach is used in reactor fuel cycle costs calculations [31] and will be applied in this paper.

9. The value of the discounting rate is taken as an average over the discounting rate values of different type and size units for appropriate conversion technology or production technology. It means that the recovery rate of an investment is considered as averaged over the applied types and sizes of these units.

By taking into account these assumptions and utilizing relationship (22) we will write the conditions of production intensity for seperate sectors. The remaining conditions, that is the financial resource and the full employment conditions will be enclosed in the constraints.

The i-th nonelectrical energy consumer sector of the h-th territorial region

Two forms of production intensity condition are distinguished for these sectors, namely when resources are utilized as:

1) primary energy carriers

$$A^h_{nli}\,X^h_{nli}=\alpha^h_{nli}\,I^h_{nli}+\gamma^h_{nli}\,K^h_{nli}+\delta^h_{nli}\,N^h_{nli}; \tag{29}$$

2) secondary energy carriers

$$A^h_{nlki}\,X^h_{nlki}=\alpha^h_{nlki}\,I^h_{nlki}+\beta^h_{nlki}\,H^h_{nlki}+\gamma^h_{nlki}\,K^h_{nlki}+\delta^h_{nlki}\,N^h_{nlki}; \tag{30}$$

where: h — index of the territorial region: nli — index of the transition path from the n-th primary energy carrier through the l-th transport sector to the i-th consumer sector; *nlki* — index of the transition path from the *n*-th primary energy carrier through the *l*-th transpor tsector and the *k*-th conversion sector to the *i*-th consumer sector; X — production intensity of the nonelectrical energy sector on the transition path chosen; I, H, K, N, — investment intensities which the *i*-th consumer sector must provide for itself, for the *k*-th conversion sector, the *l*-th transport sector and the *n*-th resource sector, respectively, on the transition path chosen; A, α, β, γ, δ — coefficients.

The time distribution of utilizing the appropriate primary energy carriers and the technologies of conversion from primary to secondary energy carriers by the *i*-th nonelectrical energy consumer sector within the appropriate time subinterval over the planning horizon T, is given by the balance equation

$$B_i^h(t)=\sum_{n\in N}\sum_{l\in L}\left\{\frac{1}{a_{nli}^h}x_{nli}^h(t-\tau_{nli})+\sum_{k\in K}\frac{1}{a_{nlki}^h}x_{nlki}^h(t-\tau_{nlki})\right\} \tag{31}$$

where: B_i — total production demand, in production units, which has to be satisfied by the *i*-th consumer sector; x — nonelectrical energy consumption, in energy units, which is needed on the transition path chosen within the appropriate time subinterval over the planning horizon T; a — the unit nonelectrical energy consumption on the transition path chosen; τ — time lags of the technology ability on the transition path choosen. To express the nonelectrical energy consumption x, in monetary units, instead of eq. (31) we have:

$$B_i^h(t)=\sum_{n\in N}\sum_{l\in L}\left\{\frac{1}{c_{nli}^h\,a_{nli}^h}X_{nli}^h(t-\tau_{nli})+\sum_{k\in K}\frac{1}{c_{nlki}^h\,a_{nlki}^h}X_{nlki}^h(t-\tau_{nlki})\right\} \tag{32}$$

where: c — unit costs of nonelectrical energy to be paid consumer sector on the transition path chosen.

The *j*-th electrical sector of conversion system of the *h*-th territorial region

$$B_{nlj}^h\,Y_{nlj}^h=\varepsilon_{nlj}^h\,J_{nlj}^h+\sigma_{nlj}^h\,L_{nlj}^h+\zeta_{nlj}^h\,M_{nlj}^h \tag{33}$$

where: *nlj* — index of the transition path of the *n*-th primary energy carrier through the *l*-th transport sector to the *j*-th electrical energy sector of the conversion system; Y — production intensity of the electrical energy sector on the transition path chosen; J, L, M — investment intensities which the *j*-th electrical energy sector must provide for itself, for the *l*-th transport sector and the *n*-th resource sector, respectively; B, ε, σ, ζ — coefficients.

The time distribution of utilizing the appropriate primary energy carriers through the *l*-th transport sector to the *j*-th electrical energy sector within the appropriate time subinterval over the planning horizon T is given by the balance equation

$$E^h(t)=\sum_{n\in N}\sum_{l\in L}\left\{\sum_{j\in J}\frac{1}{c_{nlj}^h}Y_{nlj}^h(t-\tau_{nlj})+\sum_{k\in K}E_{nlk}^{hN}(t-\tau_{nlkj})\right\} \tag{34}$$

where: E — electrical energy demand which has to be satisfied by electrical energy sectors; c — appropriate unit cost of electrical energy on the transition path chosen; τ — time lag of the technology ability to be applied on the transition path chosen; E^N_{nlk} — by product electrical energy worth of high temperature gas cooled reactors installed in the nonelectrical energy sectors of the conversion system on the nlk-th transition path.

The k-th nonelectrical energy sector of the conversion system in the h-th territorial region

$$C^h_{nlk}\, Z^h_{nlk} = \sum_{i\in I} D^h_{nlki}\, X^h_{nlki} + E^{hN}_{nlk} \tag{35}$$

where: Z — production intensity of the k-th nonelectrical energy sector on the transition path chosen; C, D — coefficients.

The l-th transport sector in the h-th territorial region

$$F^h_{nl}\, V^h_{nl} = \sum_{i\in I} O^h_{nli}\, X^h_{nli} + \sum_{k\in K} P^h_{nlk}\, Z^h_{nlk} + \sum_{j\in J} R^h_{nlj}\, Y_{nlj} \tag{36}$$

where: V — production intensity of the l-th transport sector on the transition path chosen; F, O, P, R — coefficients.

The n-th resource sector in the h-th territorial region

$$S^h_n\, W^h_n = \sum_{l\in L} T^h_{nl}\, V^h_{nl} \tag{37}$$

where: W — production intensity of the n-th resource sector; S, T — coefficients.

Constraints

The following aspects, considered as constraints, must be superimposed upon the optimal option of the transition paths, namely:

— limited financial resources,
— limited production for permissible emission of air pollutants,
— limited industrial capacity for construction of appropriate technology,
— limited condition of employment,
— limited production capacity of fissile materials in breeder reactors.

They will be specified for separate sectors, regions and the overall resource-energy system.

Sector constraints

The production intensity of separate sectors is limited because of:

1. Maximum production intensity constraints resulting from the condition of financial resources

$$Gx_{nlki}=X_{nlki}(t)-X_{nlki}(0)-\frac{1}{v_i}\int_0^t I_{nlki}(\tau)\,d\tau\leqslant 0, \tag{38}$$

$$Gy_{nlj}=Y_{nlj}(t)-Y_{nlj}(0)-\frac{1}{v_j}\int_0^t J_{nlj}(\tau)\,d\tau\leqslant 0, \tag{39}$$

$$Gz_{nlk}=Z_{nlk}(t)-Z_{nlk}(0)-\frac{1}{v_i}\int_0^t H_{nlki}(\tau)\,d\tau\leqslant 0, \tag{40}$$

$$Gv_{nl}=V_{nl}(t)-V_{nl}(0)-\sum_{i\in I}\frac{1}{v_i}\left[\int_0^t K_{nli}(\tau)\,d\tau+\sum_{k\in K}\int_0^t K_{nlki}(\tau)\,d\tau\right]+ \\ +\sum_{j\in J}\frac{1}{v_j}\int_0^t L_{nlj}(\tau)\,d\tau\leqslant 0, \tag{41}$$

$$Gw_n=W_n(t)-W_n(0)-\sum_{i\in I}\frac{1}{v_i}\left[\int_0^t N_{nli}(\tau)\,d\tau+\sum_{k\in K}\int_0^t N_{nlki}(\tau)\,d\tau\right]- \\ -\sum_{j\in J}\frac{1}{v_j}M_{nlj}(\tau)\,d\tau\leqslant 0, \tag{42}$$

where: $1/v_i$, $1/v_j$ — average investment productivities of the i-th and j-th sectors, respectively.

2. Admissible production intensities for environmental protection when fossil power plants are in service

$$Gm^1=\sum_{i\in I}X_{nli}(t)-M_1\leqslant 0, \tag{43}$$

$$Gm^2=\sum_{j\in J}Y_{nlj}(t)-M_2\leqslant 0, \tag{44}$$

where M_1, M_2 — given constants.

3. Investment intensity constraints because of limited industrial capacity for construction

$$Gm^3_{nlki}=I_{nlki}(t)-M^3_{nlki}(t)\leqslant 0 \tag{45}$$

$$\vdots$$

$$Gm^3_n=\sum_{i\in I}N_{nli}(t)+\sum_{j\in J}\sum_{k\in K}N_{nlki}(t)+\sum_{j\in J}M_{nlj}(t)-M^3_n(t)\leqslant 0 \tag{46}$$

where M^3_{nlki}, ..., M^3_n — given functions.

4. Limited production capacity of breeder reactors for fissible materials

$$Gm^4_j=\int_0^t m_j\,Y_j(\tau)\,d\tau-M^4_j(t)\leqslant 0 \tag{47}$$

where: m_j — coefficients, M^4_j — given functions.

5. Limited menpower capacities

$$Gm^5_{nlki} = u_i \, X_{nlki}(t) - M^5_i(t) \leqslant 0 \tag{48}$$

$$\vdots$$

$$Gm^5_n = u_n \, W_n(t) - M^5_n(t) \leqslant 0 \tag{49}$$

where: $u_i, \ldots, u_n$ — coefficients which determine the labour demand, $M^5_i, \ldots, M^5_n$ — given functions.

Region constraints

The production intensity within the h-th territorial region is limited because of:

1. Environmental protection

$$Gm^6_h = \sum_{i \in I} X^h_{nli}(t) + \sum_{j \in J} Y^h_{nlj}(t) - M^6_h \leqslant 0 \tag{50}$$

where M^6_h — given constants.

2. Limited manpower capacity

$$\begin{aligned} Gm^7_h = \sum_{i \in I} u^h_i \, X^h_{nli}(t) + \sum_{i \in I} \sum_{k \in K} u^h_{ik} \, X^h_{nlki}(t) + \sum_{j \in J} u^h_j \, Y^h_{nlj}(t) + \\ + \sum_{k \in K} u^h_k \, Z^h_{nlk}(t) + \sum_{l \in L} u^h_l \, V^h_{nl}(t) + \sum_{n \in N} u^h_n \, W^h_n(t) - M^7_h(t) \leqslant 0 \end{aligned} \tag{51}$$

where: $u^h_i, \ldots, u^h_n$ — coefficients which determine the labour demand in the h-th region, M^7_h — given function.

Overall resource-energy system constraint

The production intensity of the overall resource-energy system can be limited because of the national economy growth

$$\begin{aligned} Gm^8 = \sum_n Gm^8_n = \sum_n \Bigg\{ \sum_{i \in I} \sum_{l \in L} \Bigg[\int_0^T [I_{nli} + K_{nli} + N_{nli}] \, dt + \\ + \sum_{k \in K} \int_0^T [I_{nlki} + H_{nlki} + K_{nlki} + N_{nlki}] \, dt \Bigg] + \\ + \sum_{j \in J} \sum_{l \in L} \int_0^T [J_{nlj} + L_{nlj} + M_{nlj}] \, dt \Bigg\} \leqslant M^8 \end{aligned} \tag{52}$$

where: M^8 — given number.

Concluding remarks of part 1

The expansion planning, the economic model to be used in Part 2 and the set of constraints to be imposed upon the optimization problem have been presented. The optimal strategy investment problem which is considered in Part 2, will complete the optimal investment strategy of resource-energy system.

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Received October, 1976

Optymalizacja strategii inwestycji rozwoju systemu paliwowo-energetycznego

W części 1 sformułowano problem optymalizacji strategii inwestycji rozwoju systemu paliwowo-energetycznego. W części 2 (zob. z. 4) przedstawiono metodę rozwiązania tego problemu. Rozważono dwa podsystemy: węglowo-jądrowy i jądrowy. W przypadku pierwszym określono etap przejścia z paliw organicznych na substytuty tych paliw. Na przykładzie podsystemu jądrowego sformułowano problem przejścia z generacji reaktorów produkowanych obecnie do generacji samopodtrzymującej się pod względem produkcji materiałów rozczepialnych.

Оптимизация стратегии капиталовложений в развитие топливо-энергетической системы (г. I)

В первой части формулируется проблема оптимизации стратегии капиталовложений в развитие топливо-энергетической системы. Во второй части представлен метод решения этой проблемы. В первом случае определен этап перехода 2-х видов органического топлива на их заменители. На примере ядерной подсистемы формулируется проблема перехода от реакторов выпускаемых в настоящее время к реакторам саморегенерирующимся с точки зрения производства ядерного топлива.