Hierarchical Modeling in Projection Studies of the National Energy Sector Development

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***Abstract* — The focus of the paper is the evolution of methodological tools for long-term projections of the national energy sector development. The research highlights the importance of considering the growing uncertainty of the future when determining the rational hierarchy of employed economic and mathematical models. We propose adjusting their composition and the degree of aggregation depending on the projection time frame.**

***Index Terms* — energy sector, projections, uncertainty, models, hierarchy.**

I. Introduction

Long-term projection is the initial stage of the systems studies and substantiation of prospects for energy development. It is intended to outline the space of possibilities for feasible and efficient development of the national energy sector; identify the matters of concern and the bottlenecks to be addressed while pursuing such development; to set targets, framework and data required to further and detail the research when working out the energy strategy and policy, general schemes (master plans) and programs for the development of industry-specific and regional energy systems, as well as strategic plans of energy companies. Long-term projections are also crucial for laying the forward-looking groundwork in a broad area of knowledge related to the energy industry development.

The objective and significant growth of uncertainty in both external and internal conditions of the energy sector development contributes to the increased importance of long-term projections yet hinders the improvement of their quality.

Improvement and elaboration of the employed economic and mathematical models are considered to be the main strategy to build trust and confidence in projections. Significant progress has been made in this area in Russia and other countries. It seems unlikely, however, to expect further successful combating uncertainty by relying solely on greater disaggregation of modeled objects and on detailing of the external and internal links of systems and their properties. The approach to delineating and narrowing down the projection range, which sequentially identifies and solves the main problems while taking into account the uncertainty of the input data and requirements for the quality of solutions (Table 1), appears more promising.

An important role in factoring in the uncertainty when making long-term projections of the energy sector development is played by the scenario approach, i.e. model calculations under various possible states of the external environment. It is the analysis of a set of options considered to be optimal under certain conditions that basically defines the projection range («the uncertainty cone») of the long-term development of the energy sector.

Narrowing down of this range is facilitated by further improvement in methodological tools, identification of the most important problems for each time frame segment, and determination of a rational hierarchy of models to solve these problems.

II. The evolution of the applied models for projection of the energy sector development

The recognition of the important part played by long-term projections in developing strategic decisions was instrumental in the development of projections methodology based on the systems analysis methods. A major contribution to the development of such methods and economic and mathematical models as applied to the energy industry was made by the Siberian Energy Institute, Siberian Branch of the Academy of Sciences of the USSR (nowadays, the Melentiev Energy Systems Institute, SB of the Russian Academy of Sciences), where in the

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Table 1. The sequence of projection studies of the national energy sector and main problems to be solved.

Steps	Problems
1. Defining scenarios and conditions for the energy sector development	Scenarios of economic development and the state of global energy markets. Projections of the maximum possible range of energy demand and prices and that of scientific and technological advances. Assessment of temporal barriers (factoring in inertia).
2. Generating and analyzing the energy sector development options for each scenario of external conditions	Stage 1 Generating available options under maximum uncertainty of the input data. Stage 2 Narrowing down the uncertainty range through the following: models used to refine projections of the state of regional energy markets, to assess investment barriers to new capacity additions, and to factor in regional variations. Stage 3 Narrowing down the uncertainty range through the following: models for the analysis of the sensitivity of options to changes in the imposed constraints and requirements, models of detailing the features and possibilities of development of the electric power industry and other systems of individual industries. Risk assessment of energy and fuel supply options. Identifying invariants (for a given scenario).
3. Generalization of the findings of scenario studies	Delineating the overall projection range of the energy sector development (for all scenarios). Delineating the areas of invariants and areas of instability. Highlighting major strategic-level threats. Making approximate estimates of energy security indicator thresholds. Preparing supporting materials to back the working out of energy strategy and programs for the development of the energy sector industries, research activities, and technology.

1970s, the energy sector optimization model, the first in the USSR, was developed [1], and a system of models for long-term projections of energy development was created. Apart from the energy sector model, it included an input-output optimization model, a regression model of energy consumption, and a model of the requirements set by the energy sector with respect to its development that are to be met by linked industries and production facilities. A structurally similar system of models was employed back then to make the world energy projections at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria [2].

The evolution of the models and their applications as employed in projections of the energy industry development initially followed the path of gradual sophistication by way of an increasingly more elaborate representation of the economy in energy models and a more detailed description of the energy sector in models of the economy. However, by as early as the 1980s, in the USSR and other countries, the concept of employing hierarchically-built models to take account of the interactions between the energy sector and the economy gained wide acceptance, with macroeconomic models coming into ever more prominence. Abroad, it was mostly econometric models built upon the notion of the general equilibrium, while in the USSR and other planned economies input-output model served the same purpose.

The changes in the social environment and business administration rules brought about by the 1990s set the task of updating the time-honored methods and tools employed for the energy sector projections. The new economic order made it indispensable to take account of emerging energy markets and their role. Nowadays, cross-national differences in modeling interactions between the energy industry and the economy have grown much less pronounced.

As the scope of problems extended with the complexity of the tasks growing further, the tendency toward building computational systems that imply the use of capable computers and state-of-the-art information technology was becoming more and more conspicuous. The two basic approaches to the problem have come to dominate the discourse.

The first one is based on the ad hoc choice of certain models out of an available pool of various economic and mathematical models, which are indispensable for solving specific problems of long-term projections of the energy development. However, interactions between models in the systems to be built do not have to be automated. Such an approach has been implemented, for example, at the Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, where the experience accumulated over several decades helps to adapt the models sensibly and build their combinations catered to specific projections. The adjustment of input data and constraints during the controlled iterative calculations and harmonizing various models make it possible to solve the problem of considering and reconciling different optimality criteria.

An alternative approach to model integration is about striving to automate calculations and use a unified database (the integrating module) and even a common optimality criterion. This approach is exemplified by the powerful NEMS (The National Energy Modeling System) computer system [3]. It was designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) in 1993 and have since been used to estimate possible consequences of alternative cases of various (probable) energy market conditions for the energy, the economy, the environment, and the national security. NEMS is made up of over dozen models (modules), including but not limited to the following: the macroeconomic activity module, the international energy module, four supply modules; two conversion modules; four end-use demand modules, etc. The system ensures the balance between supply and demand for energy commodities for nine aggregated regions covering all the U.S.

In Russia, new modeling and information systems that are based on the integration of existing and newly built mathematical models underpinned by the cutting-edge information technology are developed to ensure systems assessment of efficiency and risks for various scenarios of the energy development, with the latter treated as an integral part of the economy. Such models are meant to enable us to capture possible consequences of decisions worked out by top-level political and economic government agencies of the country. One such system that proved successful is SCANER [4], which is being developed and maintained at the Energy Research Institute of the Russian Academy of Sciences.

Alongside vertical (cross-level) interactions, the SCANER modeling system allows for strong horizontal links, i.e. those between regional energy sector models, fuel and energy sector industries and companies, as well as between functional (that is, product demand, production and transportation, economy and financing, etc.) and temporal modules of a model of the same economic entity. Dedicated methods of horizontal harmonization of solutions obtained by optimization models have been developed to properly take account of such links. They provide for the iterative exchange of information between a given model and all the other models of the same hierarchical level on production (consumption) volumes and prices (cost-effectiveness) of each energy source used in each of the regions in each of the years of a given time frame.

The state-of-the-art computer and information technology enables us to build arbitrarily complex systems of models. It is unreasonable however not to allow for the following: large and ever-growing uncertainty of input data; dependence of required accuracy of calculations on the time frame and the problem-specific context; complexity of analyzing the results under the enormous number of variables, links, and criteria; the practicality of involving experts in some of the calculation steps. These features make us be cautious when building multi-model systems for simultaneous (joint) optimization of energy and economy development.

Such systems that feature fully automated calculations are not only hard to debug but, what is of more importance, do not lend themselves naturally to tracking the contributions of individual variables and links and interpreting the results afterward. An informal approach that implies an analysis of the information that serves as the output of one model and then fed into another model significantly simplifies the research of complex problems.

An important principle of model improvement is matching the accuracy of calculation results with the accuracy of the input data [5]. The principle is similar to the nearly proverbial Occam's razor principle and assumes building models that are as simple as possible yet capable of accounting for defining properties of the studied system that are required to appropriately solve the task under given conditions. This echoes the following quote attributed to Albert Einstein as well: «Everything should be made as simple as possible, but not simpler».

The principle of correspondence between research tools used and uncertainty of input data is fulfilled by a two-stage approach to narrowing down the uncertainty range of conditions and results by way of iterative calculations with the aid of models of various hierarchical levels employed at each temporal stage (Figure 1) and by way of reconciliation of totals in time [6]. In so doing, at the initial stage one assumes the maximum time frame (over 25 years) and the minimum number of hierarchical levels and models (see Figure 1).

The two-stage approach to making projections by moving in a retrograde fashion from the more remote future to the near future proposed herein does not preclude one from the subsequent reverse iteration of projection studies: i.e. the adjustment of long-range projections to the results obtained by more detailed analysis of a shorter time frame. Iterative calculations carried out (top-down and bottom-up) in each temporal stage make it possible to take account of features specific to the development of systems (their opportunities and requirements) of varying hierarchical levels that form the national energy system.

It seems that the composition of the models and the degree of their aggregation should depend on a given time frame, given that as the projection time frame increases, on the one hand, the uncertainty of the input data grows, and, on the other hand, the requirements for the accuracy of projections get less stringent.

An important advantage of using a hierarchy (system) of economic and mathematical models for modeling projection studies of the energy sector is the possibility of adjusting the constraints set in each model by taking into account not only direct links but also the feedback between the models during iterative calculations. A special role here is played by the inclusion in the projection workflow of regional energy market models and taking into account the price elasticity of demand, i.e. the impact of changes in the cost of energy carriers on the demand for them.

At the stage of making projections of the energy sector for the period up to 15-20 years, it is important to assess the possible macroeconomic consequences of changes that take place in the course of iterative calculations with respect to a) constraints imposed on the availability of investment resources, b) energy prices, and c) other indicators. Optimization dynamic models are used for such assessment. A concise overview of such models developed in Russia and abroad is given in [7].

In any hierarchy of models used in projections of the national energy sector development, optimization models of the energy sector play a key role. They allow tentatively singling out the balanced options of new capacity additions in the electric power industry and the fuel industry that satisfy the predefined demand for energy carriers as per a given criterion.

An overview of such a model employed at the Melentiev Energy Research Institute is presented in [8]. The balance between production and consumption of energy carrier e in region r in year t is stated in the model as follows:

$$\sum_{p\in P_r} a^t_{epr} X^t_{pr} + \sum_{r'} Y^t_{er'r} + I^t_{er} = \sum_{r'} b^t_{err'} Y^t_{err'} + \sum_{d} D^t_{edr} + E^t_{er}$$

for all $e \in 1,\ldots,E;\ r \in 1,\ldots,r',\ldots,R;\ t \in 1,\ldots,T,$

where X^t_{pr} – the production capacity of energy facility p in region r in year t; a^t_{epr} the ratio that determined the output (consumption) of energy carrier e at energy facility p in region r in year t; $Y^t_{er'r}$ the desired quantity of energy carrier e from region r' entering region r in year t; I^t_{er} energy carrier e imported to region r in year t; $Y^t_{err'}$ possible supplies of energy carrier e from region r to region r' in year t (with losses due to transportation factored in $b^t_{err'}$); D^t_{edr} – consumption of final energy carrier e by consumer categories d in region r in year t; E^t_{er} energy carrier e exported from region r in year t.

The objective function of the model is the sum of present values of all costs (for all regions and time frame segments):

$$\sum_t [\sum_r (\sum_{e,p} c^t_{epr} X^t_{pr} + \sum_{e,r'} c^t_{er'r} Y^t_{er'r} + \sum_{e,r'} c^t_{err'} Y^t_{err'} + \sum_{e,s,d} z^t_{esd^r} S^t_{esd^r} +$$
$$+ \sum_e v^t_{er} I^t_{er} + \sum_{e,a,p} \eta^t_{eapr} A^t_{eapr} - \sum_e q^t_{er} E^t_{er}) Dis^t] \rightarrow \min,$$

where $c^t_{epr}, c^t_{er'r}, c^t_{err'}, z^t_{esd^r}$ – levelized costs related to production (conversion), transportation, energy conservation of energy carrier e in region r in year t; v^t_{er} – projected prices of energy carrier e imported to region r in year t; q^t_{er} – projected prices (delivered at frontier) for energy carrier e exported from region r in year t; η^t_{eapr} - costs related to adopting and operating technologies a to reduce harmful emissions c at energy facilities p in region r in year t; E^t_{er} – the quantity of energy carrier e exported from region r in year t.

Additional assessment of the efficiency and adjustment of the obtained options may call for an analysis of the specific features and opportunities for the development of systems of individual industries of the energy sector by employing dedicated models. First of all, this refers to optimization models designed to project the development of the electric power industry [9,10]. Unlike the energy sector models, they allow more comprehensively for the modes of power production and consumption, constraints on inter-regional power exchanges, and other factors.

The weight of optimization models of the electric power industry, as well as that of other systems of individual energy industries, in the hierarchy of projection models of the national energy sector decreases as the projection time frame extends.

It is worth noting that the planning of individual energy systems can be considered as hierarchically organized. This means that when making their projections and strategically planning their development, one should make use of hierarchies of models specific to them.

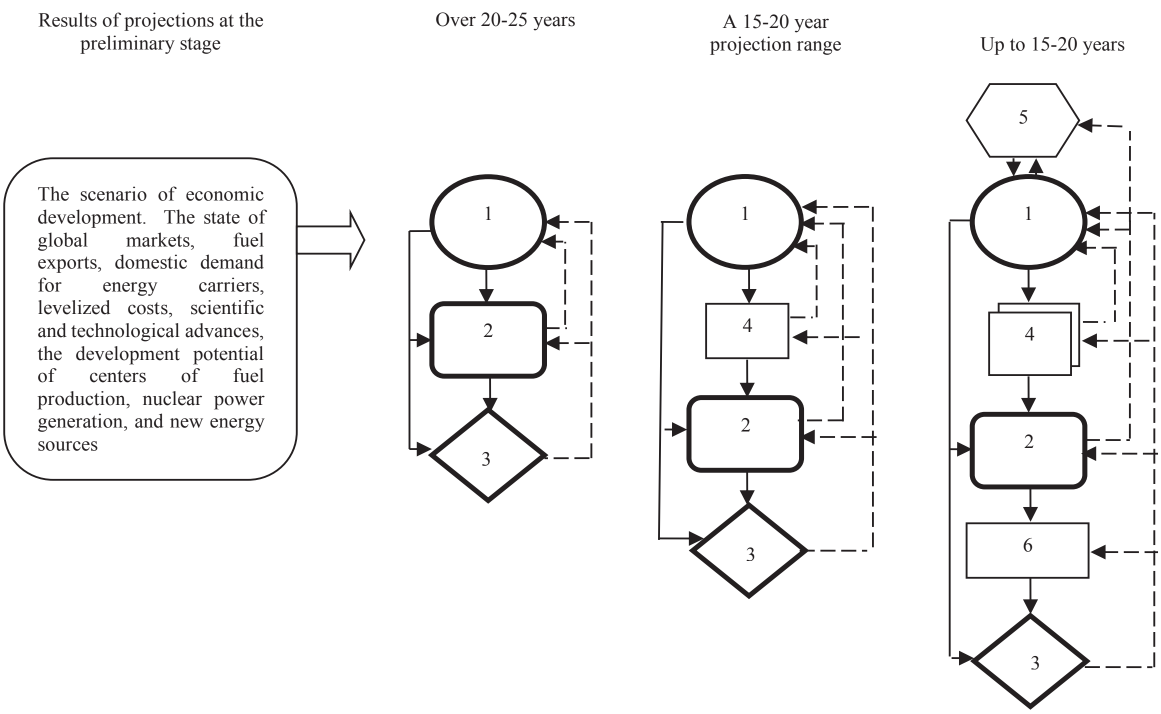

Figure 1. Hierarchy of problems and models at various temporal stages of working out and studying the options of long-term development of the energy sector
1 - The energy sector; 2 - state of regional energy markets (demand and prices); 3 - barriers and threats; 4 - industries of the energy sector; 5 - macroeconomic conditions; 6 - energy companies.

Table 2. The scope of problems where the application of stochastic models is feasible when making projections of the national energy sector development.

Model types	Projection time frame	Problems to be solved
Deterministic Primary: optimization models of the energy sector and the electric power industry	Over 20-25 years	Identification of the invariants (sustainable solutions) and the boundaries of the projection range (the uncertainty cone).
Auxiliary: disaggregated models of systems of individual industries of the energy sector, macroeconomic models, models of demand for energy carriers and their aggregated region-wise cost dynamics	Up to 20-25 years	Identification of possible issues and strategic threats. Clarification of the goals and objectives of further research
Stochastic Models of regional energy and fuel supply, regional energy markets, and development of energy companies	Up to 15-20 years	Quantitative assessment of strategic threats and energy security indicators thresholds. Price elasticity of demand for fuel and electricity. Development prospects of regional energy systems and new sources of electric energy. Risk analysis of large-scale projects and programs

III. Problems of a great number of criteria and aggregation in the hierarchy of models employed for the energy sector projections

Different levels of the hierarchy suggest using models with different criteria to come up with rational solutions. The inherent multi-criteria nature of economic systems, when it comes to the practical implementation, gives way to choosing a single most important criterion, while the rest of them serve as boundaries of the feasible range of values of alterations in key factors. In optimization models of the energy sector, such a criterion is minimum present value of costs inclusive of the investment component (levelized costs) that are required to meet a given demand for energy carriers. These prices generally do not match market prices, which distorts the real competitiveness of new production capacities. If they differ greatly, it is advisable to carry out additional model calculations based on the maximum profit criterion (considering the difference between market prices and levelized costs). In doing so, it is important to take into account the constraints on new capacity additions due to high investment risks.

When considering the prospects for up to 15-20 years, it is practical to incorporate the level of energy companies, i.e. that of potential investors and investment risk assessment, into the workflow of modeling projection studies. This allows specifying the limits set on possible new capacity additions while optimizing the development of energy systems.

Optimization models used in the energy sector projections are usually deterministic. They unambiguously identify the factors that influence the decision. Contingency calculations and analysis of sensitivity to changes in individual parameters only partially capture the uncertainty of the input data but do not take into account the likelihood of such changes. The scenario approach, which is widely used in real-life projection studies, allows assigning the probability of the covered scenarios of external conditions by experts, singling out the reference case as the most probable one. However, in doing so it does not arrive at the likelihood of other scenarios and does not take into account the interval uncertainty of the input data.

A step-by-step approach to long-term projections of the energy sector and the inclusion of regional energy supply models in the iterative workflow, along with models that simulate the behavior of potential investors, make it necessary to take into account the relative riskiness of the options under consideration as it is perceived from the point of view of potential investors. The use of stochastic models makes it possible.

In stochastic models, the input data, operating and development conditions of the modeled object are presented by random variables. The main parameters of such models are defined not deterministically, but as governed by the laws of their probability distribution [11]. In the practice of making projections, a hybrid approach can be used to combat uncertainty and take account of the stochastic nature of data, i.e. a combination of deterministic optimization models with the method of statistical tests (Monte Carlo method) [12]. Such an approach is used at the Melentiev Energy Systems Institute, SB RAS (MISS-EL models) [13] for a comprehensive assessment and risk analysis of energy supply options for individual aggregated regions.

In the projection studies of long-term development of such a complex and multi-functional system as the energy sector, it is advisable to use stochastic models in the final stages of making projections: when solving the most significant problems within each time frame segment (Table 2). The problems identified based on the analysis of the projection range include the following: quantitative assessment of investment risks, strategic threats and threshold values of energy security indicators, projections of interconnected dynamics of prices and demand in regional energy markets, assessment of the competitiveness of new technologies and fundamental changes in the make-up of electricity and fuel production and consumption. When solving these problems, one should take into account regional variations (economic, energy, environmental, and others).

In the case of large uncertainty of the input data, large size and complexity of the models behind projections, the issue of their rational aggregation arises.

IV. Conclusion

Methods of iterative information aggregation in hierarchically-built systems are mature and well-understood [14]. In the 1970s and 1980s, they underwent active development and were applied to the coordination of decisions obtained from industry-wide and regional model hierarchies of energy systems that accounted for both the production and consumption sides [15]. Such methods assume aggregation and disaggregation of all interrelated models at each iteration step. In so doing, the end of calculations is marked by achieving an acceptable level of aggregation. The latter is defined as the optimality criterion for the upper-level model taking the same value for two successive iterations. Such models include the following ones: applicable to medium-range energy sector projections: a dynamic macroeconomic model (with the maximum GDP or maximum final consumption of goods and services as the optimality criterion); applicable to long-range projections: an aggregated model of the national energy sector (with the present value of the least cost of production and transportation of energy carriers as the optimality criterion).

Rational aggregation of models employed in making real-life projections entails assessing and considering the effect of the input data uncertainty on the probable error of key variables to be projected. It is also essential to understand what magnitude of the projection error can be considered acceptable when making timely decisions (investment, managerial, or strategic).

The priority and complexity of efforts to accommodate these factors are determined by the projection time frame and the particulars of the problem. The wider the range of the input data uncertainty (which grows as the time frames increase), the greater the inevitable projection error, which thus makes it all the more justified to use more aggregated models.

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