System Inertia As A Barrier To The Acceleration Of The Energy Sector Development

Yuri Kononov*, Dmitry Kononov

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russian Federation

***Abstract* – This study is focused on the qualitative assessment of the barriers that hinder the acceleration of energy systems development. System inertia is one of the above barriers and as such, it is of tantamount importance. It is brought about by high capital intensity and material intensity of the electric power industry and the fuel industry as well as by the close direct and indirect production links they maintain with the machine industry, the iron and steel industry, and other industries that serve as their suppliers. We propose a system of performance indicators to characterize the property of inertia and the techniques for their estimation. The study reveals a nonlinear dependence of inertia on the acceleration rates of energy development. Furthermore, we elucidate the impact of imports from the industries related to the energy sector on its system inertia.**

***Index Terms* – energy sector, forecasting, inertia, indicators**

I. Introduction

High capital intensity and the inertia inherent in the energy sector industries urge us to pay due attention to their capacity to ensure the accelerated development of the Russian economy, the growth of energy consumption, and a significant increase in exports of energy resources. A possible bottleneck can manifest itself as a lack of time or that of materials, funding, and labor necessary for new capacity additions not in the energy sector itself but in its supporting industries.

* Corresponding author.
E-mail: kononov@isem.irk.ru

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The higher is the hierarchical level, the more complex grow the systems representative thereof and the more significant is their inherent inertia. Hence the more challenging it becomes to overcome the barriers that appear when accelerating the development rates and when the structure of such systems has to undergo changes.

The list of barriers depends on a specific problem and a given hierarchical level. To this end, it makes sense to distinguish between constraints and barriers that are exogenous and endogenous to a given hierarchical level (see Table 1).

Of all endogenous constraints, temporal barriers conditioned by the development inertia of energy systems are among the most significant ones.

Published research [1-6] on inertia and flexibility of energy systems saw its heyday in the USSR back in the 1980s. A similar line of research was pursued at the International Institute of Applied Systems Analysis (IIASA), Austria [7-8]. In recent years, there has been a strongly felt need to deepen and reconsider the notion of the inertia of energy systems and the importance of temporal barriers under new conditions of the development of the national energy sector and economy.

II. System inertia

Inertia is an inherent property of large developing systems. To be deemed well-grounded no projection can ignore this property. The importance of investigations into potential quantitative manifestations of inertia under changing conditions of the energy development is reflected in the works by academician Lev A. Melentiev. He defined inertia as an ability of systems to resist development understood as external and internal stimuli that target to change the previously projected pathway (development) [9], and he treated inertia as bundled with the property of flexibility as constraining the latter. By flexibility, he meant the ability of a system to change its strategy at a required rate to ensure normal development and operation under potential disturbances.

Economic inertia can arguably be characterized by the

Table 1. Energy development constraints specific to various hierarchical levels.

Hierarchical level	Internal constraints	External constraints
1. Companies, enterprises	Available production capacity (assets, technologies, labor, reserves). Financial resources. Performance of projects and their investment risks. The time required for construction and modernization.	Demand for the company's products, market prices, export and import opportunities, competition, infrastructural constraints, directives.
2. Systems of individual industries	The scale and the required time for the potential development of resource fields and new capacity additions. Available capital investments. Availability and throughput capacity of major transportation links. Constraints on the development of individual companies (as applied to new capacity additions by regions).	Volumes and patterns of demand for products of a given industry, potential for its exports, market prices, directives, assignments, and regulations.
3. Regional energy sectors	Proven resources of fuel and energy resources, required time and volumes of new capacity additions in the electric power industry and the fuel industry within the region.	Demand for fuel and energy, prices. Cross-regional energy links. Environmental and social requirements
4. The national energy sector	Production volumes and development times of major centers of fuel production, the potential for new capacity additions in the electric power industry and the fuel industry.	Demand for energy commodities, boundaries on potential exports and imports of the energy products, prices on international and domestic energy markets, indicators of national security and energy security, limits on CO_2 emissions.

efforts required to change a development trajectory (growth rates, structure, composition) of a given economic system. When applied to energy systems such efforts manifest themselves as the following indicators:

1) total (direct and indirect) capital expenditures or total costs of labor and other resources in the national economy spent on production and consumption of an additional unit (in million tce) of a given energy resource factoring in the costs of development of related industries, as well as the production and social infrastructure;

2) time required to implement all such capital expenditures and all supporting measures (inclusive of design and survey work, provision of necessary facilities on site, etc.);

3) maximum incremental increase in the production of a given energy resource that can be achieved in n years per every billion rubles of additional capital expenditures.

The latter indicator is compound in nature and is derived from the former two ones. Quantitative assessment of all of the above indicators and their presentation in the form of functional dependencies enables us to compare and rank various centers of fuel production and alternative

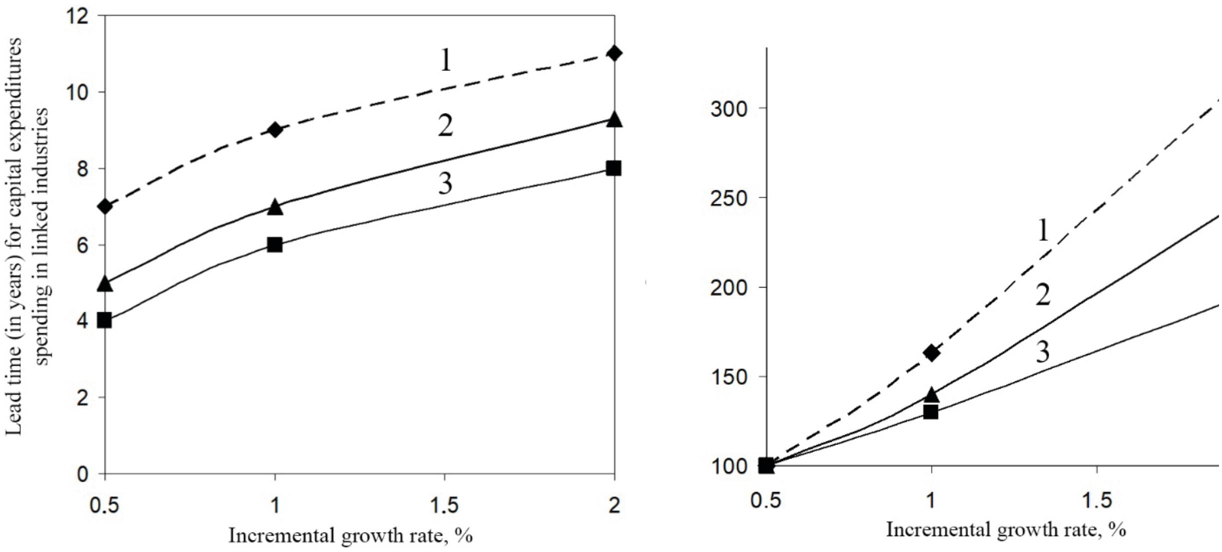

Figure 1. The general pattern of the effect an increase in incremental growth rates for the production of energy commodities has on an increase in time and capital expenditures required for the adequate development of related industries. 1 – electricity, 2 – gas, 3 – coal.
Note: exclusive additional imports of equipment and materials. Source: calculated by the authors [10].

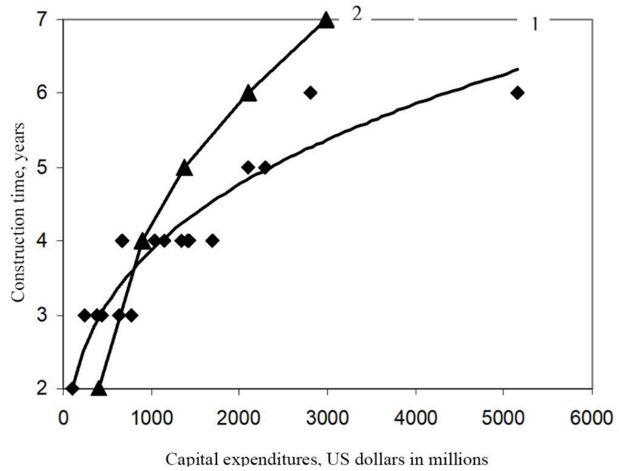

Fig. 2. The effect power plants construction costs have on the time it takes to put them into operation. 1 - in the USA, 2 - in Russia
Sources: Calculated by the authors based on [11] and [12].

energy sources based on their inertia levels.

Two complementary indicators can be applied to characterize relative inertia of the development of entire industries. These are 1) minimum time required to increase incremental growth rates of the products produced by the industry by 1 percentage point or its share in the gross output of the industry by 1 percent; 2) additional expenditures on the part of the resources of the national economy that are required to achieve this.

If one is to consider capital expenditures as a key factor that leads to changes in the structure and development rates, then total capital intensity can be understood by analogy with physics as the body weight, which characterizes the inertia of the system. The higher is the value of this indicator, the higher is the inertia.

The intrinsic inertia of the energy sector and its subsystems is made up of the inertia of new centers of fuel production and newly built energy facilities and technologies the development of which defines its prospective structure.

Obviously, inertia indicators for the development of new centers of hydrocarbon production, in addition to the features specific to a given energy production, are also influenced by region-specific features such as natural and climatic conditions, the level of development of the area, its distance from potential suppliers and consumers, the capacity of the construction base, labor balance of the district, etc. The less favorable are the regional conditions, the higher are the required direct and coupled capital expenditures for the implementation of a program.

Of all the external conditions that influence the inertia level of the energy sector, a key role is played by the level of development of related industries and the time required to produce equipment and materials to boost production, conversion, and transportation of energy resources. The implementation of large-scale projects in the electric power industry and the development of new centers of fuel production may require outpacing new capacity additions in energy-related machine industry, the iron and steel industry, the construction industry, and other industries and production units that support the energy sector. The higher is the growth rate of the energy sector industries, the higher, in general, is the number of production facilities involved in backing it and the more important is the role of remote adjacent links. Our calculations prove that additional (indirect) capital expenditures in such production facilities and their lead time grow in a non-linear way as the energy sector development accelerates (see Figure 1).

The non-linear growth of the time required for construction as directly related to the increase in required capital expenditures is furthermore proved by Figure 2 based on Russian and American data on capital expenditures (in 2009 prices) and time limits for construction of power plants of various types.

The energy sector development inertia is related to the inertia of the entire economy. The higher is its ability to make maneuvers with financial and labor resources, to change the structure of its industries and promptly respond to changing situation and state of international markets, the easier it is to ensure required changes within the energy sector and its related industries. On the other hand, the energy industry enhances the flexibility of the economy by lowering its inertia.

2. Methods and findings of the research into the temporal barriers and inertia of energy systems

The input-output IMPAKT model was developed as early as back in 1975 to enable the study of the inertia property. The model formalized the process of retrograde unfolding (i.e. from the future back to the present) of links of various levels from a given energy facility to production facilities that ensure its development. A shortcoming of this model was that it failed to account for expected economic conditions. To a certain extent, this issue is addressed by the IMPAKT-2 system of models developed at the Melentiev Energy Systems Institute, SB RAS (see

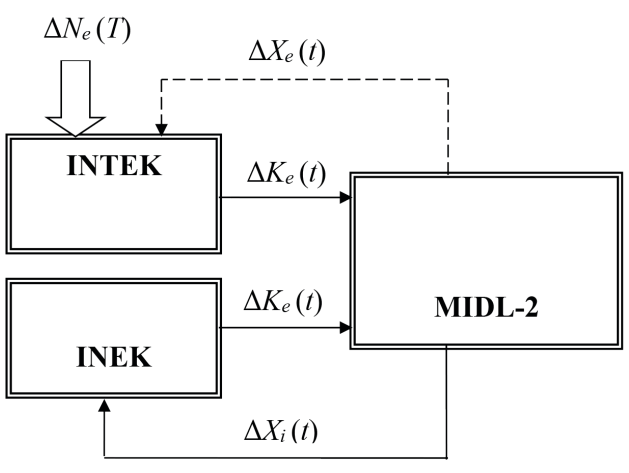

Fig. 3 The information flow diagram of the IMPAKT-2 model.

Figure 3). Its software implementation is made up of three modules: INTEK, INEK, and MIDL-2

MIDL-2 is an updated version of MIDL, a well-established dynamic optimization macroeconomic model [13] of the input-output type. The new version of this model takes into account the annual dynamics of economic development unlike the earlier version that was limited to the temporal resolution of five-year periods within the 30-year long timeframe. The model describes mutual production links between 29 branches of the national economy and between production and non-production industries via the consumption of goods and services, as well as investment links and export-import links.

INTEK is a model employed for the assessment of required dynamics of direct capital expenditures for the construction of new energy facilities (inclusive of the required infrastructure) that are part of a given development option. To this end, the model allows for standardized time limits for construction and the distribution of equipment costs and mechanical completion costs over the span of all years starting from land-use planning and development to commissioning and start-up of the facility. The model allows aggregating certain variables and presents them in a way that suits their use in a macroeconomic model.

The INEK model determines the dynamics of capital expenditures for related industries and production facilities. Requirements for their development rates are determined upon obtaining a corresponding solution from the MIDL-2 model.

IMPAKT-2 modeled calculations are performed as per the following iterative procedure under the assumption that the reference case of the development of the economy and the energy sector is pre-defined [10]:

1. MIDL-2 is calibrated so as to match the reference case.
2. The INTEK model then calculates the dynamics of new capital expenditures based on a pre-defined case of new capacity additions in the energy sector or one of its subsystems. The respective additional demand for equipment and construction and installation work are then fed into MIDL-2 together with data on the required increase in the energy sector production volumes in year T.
3. The solution provided by MIDL-2 and its comparative analysis against the reference case makes it possible to determine the rate of required additional development of related industries (first-level linking), as well as the corresponding increase in demand for energy commodities.
4. These data ($\Delta X_i\ (t)$) are fed into the INEK model that calculates additional capital expenditures required in related industries.
5. In the case of a significant increase in the fuel and energy demand in related industries, INEK is used to detail the capital expenditures required by the energy sector.
6. The results of calculations in stages 4 and 5 are then transferred to MIDL-2 in order to detail the dynamics of the additional development required of the economy relative to the reference case and to identify more remote linking levels.

By varying the product imports of various industries in MIDL-2, one can assess their impact on the inertia level (i.e. the required look-ahead development of related industries and its scale).

The following IMPAKT-2 model calculation results for a simplified case study provide an overview of potential impacts on the scale and time limits of required additional development of various branches of the economy, on the increase in the electric energy production and equipment imports. The scenario of the development of Russian economy and energy industry in which electric energy

Table 2. The effect of 60% imports of equipment on lowering the demand for products of related industries and coupled capital expenditures.

Industries	Decrease, %	
	gross output	capital expenditures
Machine industry	79	75
Construction industry	7	3
Oil and refinery industry	21	15
Gas industry	9	10
Coal industry	8	1
Iron and steel industry	54	50
Chemical industry	49	43
Construction materials industry	11	3
Transportation industry	29	20
Other industries	25	20
Total	**34**	**17**

production reaches the 1.5 trillion kWh by 2030 was used as the reference case. As its alternatives, we also studied the growth of electric energy production by additional 5 and 15 percent in 2026 to 2030.

Our calculations suggest that total capital expenditures of related industries, given no equipment and materials imports, can exceed direct investments in the electric power industry by 1.2 times under additional growth rates of the electric energy production by further 5%, and by 1.35 times under the growth rates of 15%. The share of the gas industry and other fuel industries in the overall composition of additional capital expenditures for related industries, the transportation industry, and the telecommunications is 15-22%, the construction industry accounts for 12-19%, the machine industry is 2-6%, the iron and steel industry is 2-3%, while the rest of the industries make up 11-12% altogether.

It is essential that a significant share of capital expenditures, the required increase in the demand for industrial products and services take place in the years prior to the surge in electricity production. Based on our calculations, the increase in the demand for industrial products, construction and installation work, the transportation and tertiary services manifests itself 5 to 10 years prior the required 5 percent increase in the electricity production and by 10 to 15 years and more in the case when such incremental growth increases up to 15 percent.

Imports of required equipment contribute to a notable decrease in the level of inertia by eliminating remote linking levels. This is illustrated by the data in Table 2 that reflect the results of calculations for the case of the incremental increase in the electricity production by 15 percent subject to the constraint that makes 60% of additional demand for the machine industry products (relative to the reference case) satisfied by imports in the time period from 2020 to 2030. The calculations suggest that the additional demand for the products of all related industries decreases by 34 percent. Here, most drastic (by 50 percent and more) is the decrease in the required production of ferrous and non-ferrous metals and chemical products. Freight turnover and demand for petroleum products fall by 21-29 percent (exclusive of gas pipelines). Required production output by the machine industry decreases over the entire period more than the volumes of additional imports of energy equipment due to the decrease in the demand for related capital expenditures. In this case, the lead time at the beginning of the investment process decreases as follows: by 8 to 12 years in the machine industry, by 5 to 10 years in the iron and steel industry, and up to 5 years in other related industries

III. Conclusion

It follows from the above that the inertia inherent in the energy sector development can be properly assessed only when viewed together with the entire economy, whereas an analysis of the inertia inherent in the development of individual centers of fuel production requires due consideration of its role in the national energy sector.

The present study outlines an approach to quantitative assessment that targets such inertia indicators as the timing and the scale of the required look-ahead development of the industries related to the energy sector alongside the corresponding capital expenditures. The method can prove instrumental in elaborating available approaches to a comparative ranking of the energy sector development options as based on the feasibility criterion [14]. Evaluation of risk in individual capital investment projects should serve as a vital part in the process of arriving at such a comprehensive criterion. This analysis on a par with addressing the issue of energy systems inertia is an integral component of assessing quantitatively the robustness of available options under changing conditions [15].

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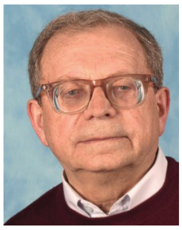

Yuri D. Kononov - Doctor of Economics, Professor, Honored Worker of science of the Russian Federation, chief researcher of Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Russia, Irkutsk. His research interests are modeling and research of interaction between energy and economy; methods to enhance the validity of long-term forecasts of energy development.

Dmitry Yu. Kononov - Ph. D., Senior researcher of Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Russia, Irkutsk. His research interests are consideration of the impact of the uncertainty factors on the methods for the evaluation of strategic threats to power industry development.