Competitiveness of Export-Oriented Systems of Long-Range Energy Supply

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***Abstract* — The paper examines process chains including production, transport, and conversion of energy resources from Siberia and the Russian Far East to Asian countries. The study aims to find the most effective ways to supply energy to end consumers at various distances. The options considered include pipeline transport of natural gas from eastern regions of Russia to Asian countries; rail transport of coal from Russian export-oriented deposits to Asian countries; natural gas conversion into methanol, with methanol transport through pipelines of various diameters to Asian countries; and coal conversion into methanol, with methanol transport through pipelines of various diameters to Asian countries. Optimization is performed using previously developed mathematical models.**

***Index Terms* — methanol, natural gas, coal, export, Russia, Asia, mathematical modelling.**

I. Introduction

In light of the current global situation, Russia has to explore new avenues to export minerals, primarily coal, natural gas, and oil, while also enhancing its role in Asian countries [1–3].

When considering the options for transporting the energy of fossil fuels from export-oriented deposits in Russia's eastern regions to Asian countries, the problem arises of how to find the best ways to “deliver” the energy to the end users. This is due to the significant volume to be transported and long range [3–8].

Modern research focuses on modelling global trade [9], modelling energy systems [10], redistribution of natural gas flows [10], analysis of scenarios for the influence of external factors on the economies of countries [11–13] and on energy prices [14, 15], the influence of geopolitical events and mineral exports on the transition to renewable energy [16], and the impact of export activities on the environment [9, 17].

A computable general equilibrium model of world trade is used in [9] to quantify the possible impact of economic sanctions.

A detailed mathematical model is proposed in [10] to predict the movement of gas volumes through the pipeline of the European gas market.

The main components of a methodological approach are delivered in [11] to assess the level of significance of critical energy facilities on the example of individual shutdowns of the most important facilities of the Russian gas transmission network. The paper also presents approaches to modelling the energy sector of the country and its constituent energy (gas, electricity, and heat) systems.

Possible invariant measures aimed at reducing gas shortages for consumers in the case of emergencies at critical facilities of the gas industry are discussed in [12]. The study focuses on Russia’s Unified gas system,

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providing a logical unfolding of the topic of searching for and identifying critical components of the system.

Shifting to gas in the Asian regions of Russia is presented in comparison with this process in the European part of the country. The level of gas infrastructure expansion in the Asian regions of Russia is far behind that in the European regions of the country [13].

The comprehensive approach proposed in [14] offers a deeper understanding of the interplay between energy trade dynamics, the updated NDCs, and carbon emissions. The study contributes to a more profound comprehension of the evolving fossil energy trade landscape and its implications for carbon emissions.

A global computable general equilibrium model [15] proves the impact of the Russian natural gas embargo on the economies of Russia and the EU.

Authors of [16] conclude that discontinuing imports of Russian energy resources would present a challenging scenario for the European Union. They propose using domestic supplies and reducing demand.

The paper [17] presents an investigation of whether financial development can reduce the export concentration in regional context, corroborating the role of the World Trade Organization membership, sanctions and investment potential. The Method of Moments Quantile Regression to analyse panel time-series data.

The time evolution of the amplitude of chaos for the Historical Prices of the Title Transfer Facility and the United States Natural Gas Fund commodities are analysed both before and during the special military operation [18]. Methods include Phase Space Reconstruction in Four-dimensional Euclidean Spaces from time series and Spearman Correlation between chaos intensities, elapsed time and prices.

In [19], the impact of geopolitical risk (GPR) on natural resources is evaluated by employing monthly (from January 1990 to January 2023) and daily (from 3rd January 2022 to 31st March 2022) data. The outcomes using wavelet QQ and novel Bayesian structural model reveal that GPR has a more profound impact on oil prices, natural gas prices, and gold prices (in a range of lower to upper quantiles) exhibiting that they are more sensitive to geopolitical uncertainties at all levels.

The study [20] examines the interplay between Russian mineral exports and renewable energy generation, taking into account geopolitical risks, within both the global and Chinese contexts. Utilizing the cross-quantilogram approach, this study reveals a positive spillover effect of Russian mineral exports on global and Chinese renewable electricity production, across various time frames, including monthly, quarterly, bi-annual, and annual memories.

The impacts of trading partners' environmental regulation on the export volumes of the Russian regions is analyzed using panel data covering about 140 000 observations in 84 Russian regions and 204 countries. The Gravity Model of international trade and Heckman Sample Selection methodology are employed [21].

There are various energy transmission and conversion options that require engineering and economic studies. These are pipeline transport of natural gas; rail transport of coal; conversion of natural gas and coal near export-oriented fields into synthetic liquid fuels (SLF), such as methanol, and its transport by methanol pipelines; and others [7, 8, 22, 23]. Options based on the conversion of gaseous and solid fuel into liquid fuel offer the advantage enabling pipeline transport of liquid fuel, which is much more economical for long distances and large scale compared to pipeline transport of natural gas or rail transport of coal [23].

Options for energy transport rely on both conventional well-established technologies (pipeline transport of natural gas or liquid fuel, rail transport of coal) and technologies that are novel in terms of the possibility of their large-scale adoption. This applies primarily to technologies for large-scale conversion of solid and gaseous fuels into synthetic liquid fuels. The conversion and subsequent SLF pipeline transport provides a lower price per unit of energy for the end user, while retaining the same profitability of the project (or an increase in the profitability while retaining the same competitive price). This process also offers enhanced performance of the energy carrier for the end user (the possibility of using it as a motor fuel, inexpensiveness of storage and transport in small batches, environmental friendliness, and others).

One promising synthetic liquid fuel is methanol. Methanol is a versatile intermediate for the production of a wide range of important chemical products. It is also an environmentally friendly liquid fuel that can be easily transported and stored. The main disadvantages of existing processes of converting fossil fuels into synthesis gas, followed by subsequent methanol production, are low thermal efficiency and large capital investment. This can be avoided by establishing systems for methanol and electricity co-production (MEC) based on the processes of coal gasification or conversion of natural gas and subsequent synthesis of methanol. In this case, the high-temperature heat of the gasification products as well as the heat and energy of the combustible purge gases of the synthesis process are utilized in the power generation plant. This is why fuel and electricity co-production systems are economically feasible and energy efficient.

It is important to emphasize that the above energy transport options can be considered as process chains that include series-connected links. Comparison of chains will be objective only if the parameters of the links in each process chain are optimized. Note that simultaneous optimization of the parameters of all links in the chain is a challenging task.

The Melentiev Energy Systems Institute SB RAS has developed an approach to optimize process chains. This approach involves a sequential optimization of each link in the chain. The criterion is the minimum price for the output product of each link. The optimization process takes into account a fixed level of internal rate of return on capital investment across all links and chains and the price of the output from the previous link, which is obtained during its optimization.

Our previous studies focused on power supply chains for remote consumers with various types of generation. Some models were borrowed from previous studies and then improved by increasing accuracy and updating the initial information [24].

II. Formulation of the Problem

As noted earlier, this work employs the approach to process chain optimization, which was developed at the Melentiev Energy Systems Institute SB RAS.

A mathematical problem statement of sequential optimization of links in the process chain can be represented as follows

$$\min_{x^i} c_{out}^i \tag{1}$$

subject to:

$$H^i(x^i, y^i, z^i) = 0, \tag{2}$$

$$G^i(x^i, y^i, z^i) \geq 0, \tag{3}$$

$$K^i = K^i(x^i, y^i, z^i, s^i), \tag{4}$$

$$U^i = U^i\left(x^i, y^i, z^i, c_{in}^i\right), \tag{5}$$

$$Q_{in}^i = Q_{in}^i(x^i, y^i, z^i), \tag{6}$$

$$Q_{out}^i = Q_{out}^i(x^i, y^i, z^i), \tag{7}$$

$$Q_{ac}^i = Q_{ac}^i(x^i, y^i, z^i), \tag{8}$$

$$c_{out}^i = Y^i\left(K^i, U^i, Q_{in}^i, c_{in}^i, Q_{out}^i, Q_{ac}^i, c_{ac}^i, IRR_z, \theta^i\right), \tag{9}$$

$$c_{in}^{j+1} = c_{out}^j, \tag{10}$$

$$Q_{in}^{j+1} = Q_{out}^j,\ j = 1, \dots, N-1, \tag{11}$$

$$\underline{x^i} \leq x^i \leq \overline{x^i}, i = 1, \dots, N, \tag{12}$$

where the subscript *i* stands for the number of a link in the process chain; c_{out}^i is energy carrier price at the output of the *i*-th link; H^i is system of equality constraints of the *i*-th link; x^i is vector of independent parameters of the *i*-th link to be optimized; y^i is vector of dependent calculated (from the system H^i) parameters of the *i*-th link; z^i is vector of input data (strength characteristics of materials and equipment characteristics that are not subject to optimization); G^i is system of inequality constraints of the *i*-th link, which sets boundaries within which its parameters can be changed; K^i is capital investment in equipment of the *i*-th link (in general case, a vector with the components that specify capital investment by year of the calculation period); s^i is specific cost characteristics of equipment; U^i is operating costs of the *i*-th link (in general case, a vector specifying costs by year of the calculation period); c_{in}^i is energy carrier price at the input of the *i*-th link; Q_{in}^i, Q_{out}^i are energy carrier consumption at the input and output of the *i*-th link respectively; Q_{ac}^i , c_{ac}^i are consumption and price of the energy carrier co-produced by the *i*-th link and consumed locally, i.e., without entering the (*i+1*)-th link; IRR_z is the given (for all links and all chains) value of the internal rate of return on investment; $\theta^i$is vector of economic parameters (rates of different taxes, etc.) used to calculate *IRR*; *N* is number of links; $\underline{x^i}$, $\overline{x^i}$ are vectors of minimum and maximum possible values of parameters to be optimized. The problem is solved by the method of mathematical modelling.

III. Results and Discussion

The considered potential options for energy supply to remote consumers in Asian countries are as follows:

- Pipeline transport of natural gas from eastern regions of

Russia to Asian countries.

- Rail transport of coal from export-oriented deposits to Asian countries.
- Conversion of natural gas into methanol, transport of methanol through pipelines of various diameters to Asian countries.
- Conversion of coal into methanol, transport of methanol through pipelines of various diameters to Asian countries.

Let us highlight the key distinctive features of the above energy transport options. Capital investment in gas pipelines is directly proportional to their length, while the methanol transport options have a significant part of capital expenditures independent of the transport distance, which are capital outlays on methanol production. At the same time, the specific cost of line pipes of methanol pipelines is significantly lower (per unit of equivalent amount of energy transmitted) than that of gas pipelines.

Conversion of natural gas and coal into methanol is assumed to be done using the systems for combined production of methanol and electricity [23]. Methanol pipelines with diameters of 1020 mm and 1220 mm are considered for long-distance methanol transport. The price of natural gas in Siberia and the Far East regions is assumed to be equal to 120–150 USD/1000 m^3, the price of coal - to 50–70 USD/tce based on [25, 26]. Specific costs for rail transport of coal are 35–40 USD/tce-1000 km) [27]. The options in question differ significantly in the consumed amount of primary energy resource. The transport of natural gas through a 1420 mm pipeline can accommodate 36 billion m^3 (40 million tce) per year. The

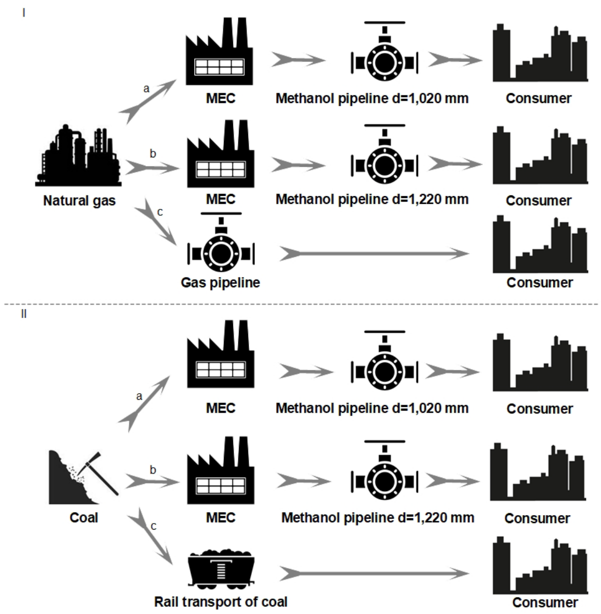

Fig. 1. Process chains of production and transport of energy resources from Siberia and the Russian Far East to Asian countries.

TABLE 1. Prices of Energy Carriers at the End of Process Chains, Depending on the Options for Conversion and Transport of Energy Resources, USD/tce

Options for conversion and transport of energy carriers		Transport distance		
		3 000 (km)	4 500 (km)	6 000 (km)
Pipeline transport of natural gas from Russia's eastern regions to Asian countries through a 1420 mm diameter pipeline	1a – Gas price 120 USD/1000 m^3	171	211	257
	1b – Gas price: 150 USD/1000 m^3	197	238	284
Rail transport of coal from Siberian and Far East deposits to Asian countries	2a – Coal price: 50 USD/tce	170	230	290
	2b – Coal price: 70 USD/tce	190	250	310
Methanol production from natural gas fields in eastern regions of Russia, pipeline methanol transport to Asian countries through a 1020 mm diameter pipeline	3a – Gas price: 120 USD/1000 m^3	206	221	235
	3b – Gas price: 150 USD/1000 m^3	257	272	288
Methanol production from natural gas fields in eastern regions of Russia, pipeline methanol transport to Asian countries through a 1220 mm diameter pipeline	4a – Gas price: 120 USD/1000 m^3	199	210	222
	4b – Gas price: 150 USD/1000 m^3	251	262	274
Methanol production from coal deposits in eastern regions of Russia, pipeline methanol transport to Asian countries through a 1020 mm diameter pipeline	5a – Coal price 50 USD/tce	196	210	224
	5b – Coal price 70 USD/tce	234	249	264
Methanol production from coal deposits in eastern regions of Russia, pipeline methanol transport to Asian countries through a 1220 mm diameter pipeline	6a – Coal price 50 USD/tce	190	200	211
	6b – Coal price 70 USD/tce	227	238	250

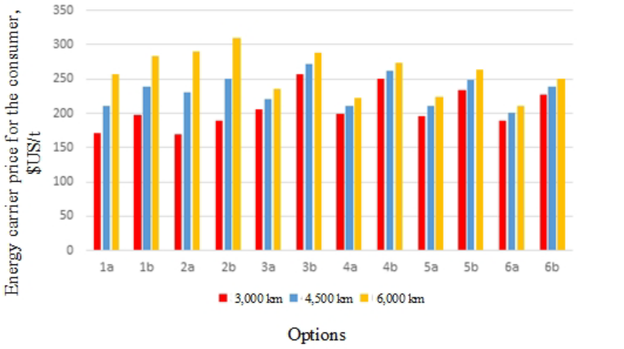

Fig. 2. Comparative performance of options for converting and transporting energy resources.

energy equivalent of methanol transmitted through a 1020 mm pipeline is 35 million tce per year, and through a 1220 mm pipeline – 70 million tce per year. Coal can be delivered by rail in amounts of up to 16–20 million tce per year.

Figure 1 shows the technologies considered in this study for energy production and transport. Table 1 shows the optimization results of the options for energy supply to consumers in Asian countries.

Figures 2 and 3 show the comparative economic feasibility of options for converting and transporting energy resources as a function of the transport distance.

The lowest unit price of final energy for an energy transport distance of 3 000 km is provided by the following: for options with coal as the initial energy carrier – its rail transport; for options with natural gas as the initial energy carrier – its pipeline transport. Options with the conversion of coal and natural gas into SLF when transported over 3 000 km prove inferior to direct transport of these energy carriers (without considering the higher methanol cost for the consumer). The lowest unit price of the final energy for the energy transport distance of 4 500 km is provided by the following: for options with coal as the initial energy carrier – coal conversion into methanol with its subsequent transport through a 1 220 mm diameter pipeline; for options with natural gas as an energy carrier – pipeline transport of gas and gas conversion into methanol with its subsequent transport through a 1 220 mm diameter pipeline. Note that with cheap coal, the unit price of final energy of methanol from coal is lower than the unit price of final energy from cheap gas.

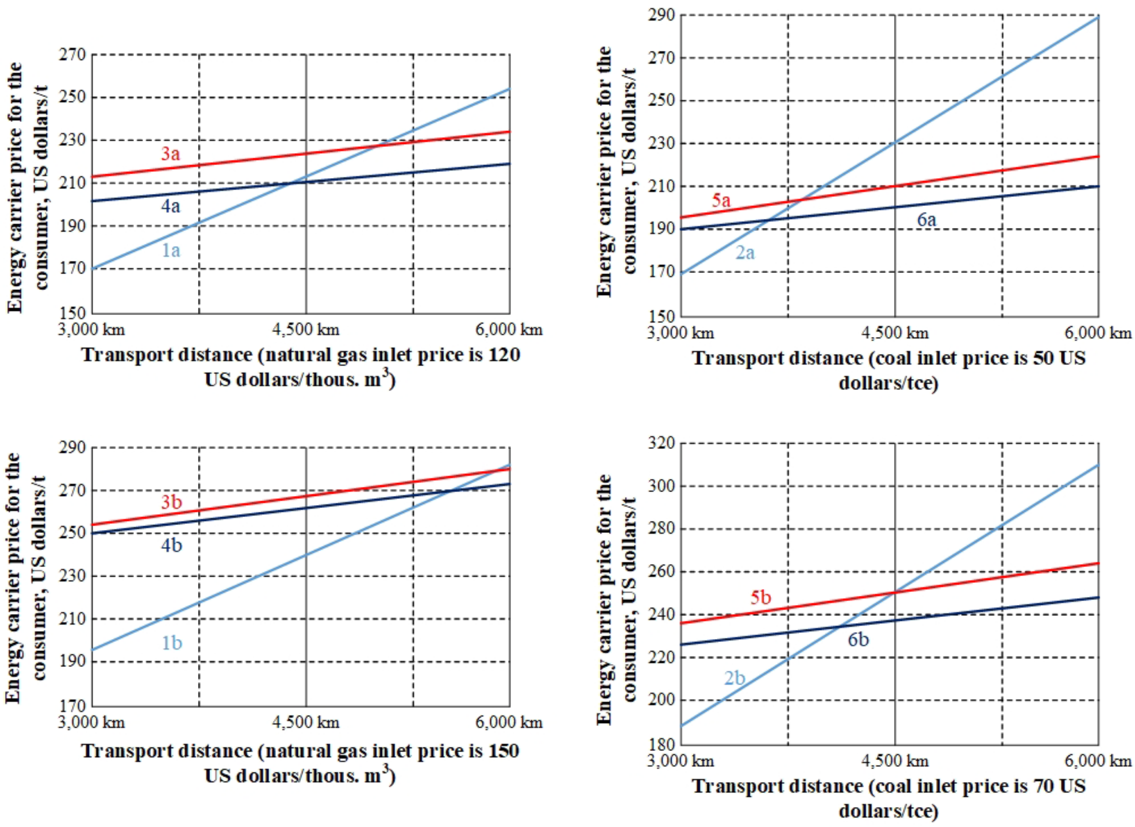

Fig. 3. Comparative performance of natural gas energy and coal energy transport options.

IV. Conclusion

The study examined the process chains of long-distance transport of energy carriers (natural gas, coal, and methanol from them) from Russia to Asian countries. Optimal options are obtained for various distances.

It is important to emphasize that in recent years, several large plants for the production of methanol from coal based on gasification technologies have been commissioned or are about to be commissioned in Asia. To this end, they use the technological solutions provided by world's leading companies: Shell, Siemens, and General Electric. In the current context, there are promising opportunities for the Russian Federation to enhance its existing technologies and collaborate with Asian organizations on combined fuel production projects.

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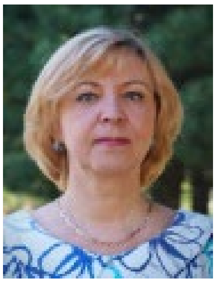

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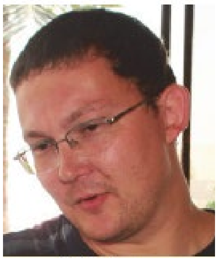

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