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The Balance and Optimization Model of Coal Supply in the Flow Representation of Domestic Production and Imports: The Ukrainian Case Study

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Abstract: The successful supply of an economy with coal fuel, for a country that carries out its large-scale extraction and import, is a complex production and logistics problem. Violations of the usual supply scheme in conditions of crises in the energy markets, international conflicts, etc., lead to the problem of simultaneous restructuring of the entire supply scheme. This requires changes in the directions and capacities of domestic production and imports. In this article, the above problem is solved by the economic and mathematical model of production type. The developed model includes subsystems of domestic production and import supply. The results of modeling economy supply with thermal coal for different values of demand are given. The model was used to determine the amounts of coal production for Ukraine with the structure of the coal industry of 2021 and under the condition of anthracite consumers' transformation to the high volatile coal. Simulations have shown that eliminating the use of anthracite requires the modernization of existing coal mines. Under those conditions, the import of high volatile coal will amount to 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coking coal imports will be 5.46 million tons, 5.151 million tons, and 7.377 million tons in 2025, 2030, and 2035, respectively.

Keywords: coal supply; model of production type; flow representation; domestic production and imports

1. Introduction

Energy balances in Ukraine are currently undergoing significant and large-scale changes, caused by a number of extraordinary influencing factors [1]. Namely, first of all, a military-political crisis is ongoing in the state, which is marked by the occupation of the country's territories, the violation of the usual traditional supply schemes, the general economic recession [2], and the related reduction in demand for fuel products, both in the energy sector and in industry, rural economy, transport, and the social sphere [3–8].

Another factor of changes in the supply of energy resources is the global tendency to reduce the consumption of carbon-containing types of fuel, which has gained significant strength in recent decades against the background of the rapid development of technologies of renewable energy sources (RES) [9–13], and systems of their accumulation and storage [14]. Technological progress in these energy sectors has led to a significant increase in the practical application of RES and their relatively safe integration into existing power systems, with minimal disruptions to their operation modes [15,16].

Under these circumstances, almost all types of coal fuel have become one of the most important groups of energy carriers for Ukraine, which has been successfully displaced from economic circulation. Chronologically, the state was the first to experience a significant shortage of coal of anthracite grades [17–19], which arose due to the occupation of certain areas of the Donetsk and Luhansk regions, and the country was forced to transfer almost all power units of thermal power plants to the consumption of coal of the gas group [20–27].

Recently, studies have appeared that directly point to Russia's geopolitical claims as a direct and already existing threat to Europe's energy security. For example, in [21,22] it is shown that many countries in the European Union imported a significant amount of energy resources from Russia. At the same time, the share of imports from Russia for individual countries reached 50%. The article [23] indicates that one of the motives for starting a military conflict on the territory of Ukraine may have been due to mineral deposits, including coal, oil, and gas. Article [23] also shows that the geopolitics of Russia in recent years has been aimed at controlling energy facilities in the republics of the former USSR, in particular in Moldova and Transnistria. In support of this, it is important to note that, since 2014, part of the coal mines have been located in territories that the Ukrainian state authorities do not control, but which have been supported by Russia. With the start of the military invasion in February 2022, the number of such mines has increased. It is estimated [24] that the share of mines located in the territory controlled by Russia has reached 63%.

As a result of the development of the military confrontation and the expansion of the territories of hostilities, energy-intensive enterprises, in particular metallurgical enterprises, were damaged or destroyed, which caused a decrease in demand for the coking group of coal brands. Correspondingly, the amount of imports of coking coal of grades and quality indicators necessary for metallurgy, which are not mined in Ukraine, also decreased [28–30].

In addition, ensuring the currently available consumption volumes no longer requires the intensive work of all the country's mines at the level of their established production productivity. Moreover, the urgent need to support the global trends of low-carbon development, as well as the extremely high cost of production of coal-mining enterprises with practically exhausted reserves and a high depth of occurrence, gives rise to the problems of the simultaneous assessment of the structure of domestic mining enterprises, and the appropriate directions for the development of the coal fuel base in the country, as well as all possible directions of external supply of coal products. An important aspect to take into account is the import requirements and opportunities of the Ukrainian economy for coal products [31,32] in particular the differentiated need for them in the energy sector and industry, taking into account physicochemical characteristics, brands, quality indicators [33–37], etc., as well as the structure and volume properties of logistic supply schemes [38,39].

The authors previously developed various scenarios for the development of the coal industry in Ukraine [40], which included not only an assessment of the prospective volumes of coal production for various purposes but also the cost of its production. After the start of the military conflict, as mentioned above, the share of mines controlled by the Ukrainian authorities decreased. In this regard, it becomes impossible to estimate the possible volumes of coal production in the future due to insufficient data on the state of such mines and the possibility of their further functioning. In such a situation, in order to meet the needs of thermal power plants, most of the power units in Ukraine operate on coal fuel, so it is necessary to import missing volumes. At the same time, considering the coal balance as a whole, especially in the context of the tasks of general energy supply by all types of fuel and energy resources, forecasting the volume of supply of energy carriers under conditions of economic growth, their economically expedient or forced mutual substitution, as well as taking into account energy security criteria, it is necessary to be able to review the composition of the mining capacities of the coal industry, its expansion through the construction of new mines, as well as the restoration of the previously closed unprofitable mining enterprises [41–44]. The usual logistics schemes will also be subject to revision in connection with political and security (military) restrictions on import supply routes.

Thus, in the study of the circulation of coal products in the country's economy as a closed technological process, efforts to increase the efficiency and safety of the production and use of all types of energy and raw coal, taking into account the balances of other energy carriers, especially in the energy sector, leads to the need for simultaneous interconnected consideration of all links of this process, which are usually described by specialized balance and optimization mathematical models of various levels of detail [45–56], which allow determining the most appropriate operating conditions of a coal complex based on certain criteria. Among such criteria is the total volume of domestic coal production, its individual grades, and technological purpose, the volume of production of a separate coal-mining enterprise, and the volumes and directions of supply of coal products that satisfy the requirements for standard fuel [57,58], electricity, and heat generating enterprises of thermal energy, costs for such fuel supply, volumes of environmental pollutant emissions by thermal power plants [59–62] due to coal burning, volumes of forced coal imports and corresponding indicators of energy security [63], etc.

In this way, determining the appropriate volumes and directions of coal supply to the economy appears as a multi-product production and network-transport problem with safety restrictions that bind the volumes of these subsystems. The need for a formal presentation of such a supply system in this work is provided by an economic model, which provides for the representation of production facilities and the supply network in a single way in the form of production activities: vector-matrix structures of the production type model [64,65]. Building such a model for the coal supply system of the economy is an important task, given the need to combine such aspects of coal supply as multi-product production technologies, and the structure of the transport subsystem and is the main goal of this work.

The optimal volumes of domestic production and importation of all types of coal products needed in the economy, obtained from its solutions, satisfy the requirements both for volumes and for the necessary levels of security of supply. At the same time, the results of the calculations can serve not only to determine the amount of necessary income but also to develop a system of measures for the transformation of the energy sector and other industries that consume coal, in the direction of a gradual transition to a stable and guaranteed coal balance.

In particular, recent changes in the structure of the mining sector of the fuel and energy complex of Ukraine, caused by reasons of a political and economic nature, have led to a significant, and for some brands of coal, complete reduction in production [3,4]. Territorial separation of mining enterprises producing anthracite groups of coal currently make it impossible to reliably and uninterruptedly supply this type of fuel to consumers from sources of own production. In this state of the industry, meeting the needs of consumers in anthracite coal is possible only through imports.

From the point of view of energy security requirements [66,67], such a state of the coal supply system is acceptable, in which supply from the country's own sources prevails over import volumes. Such a state can be achieved by carrying out measures to modernize or reconstruct existing mining enterprises that have the potential to increase production capacity in order to increase the level of domestic production [68,69].

Summarizing all of the above, the novelty of this paper is its new approach to the entire coal supply–transformation–consumption system representation. First, a certain network scheme of its production and transportation links is created, which in the most uniform way describes all technologically different aspects of coal circulation in the economy. Next, this associated network is used to create a matrix representation of the system in the form of sequential production activities, composed of the technological matrix introduced by L.V. Kantorovich.

Despite the fact that this article presents the system of coal supply to the Ukrainian economy, the application of the proposed model may be highly valuable for other countries, the share of coal in the balance of which is significant. In particular, the presented model may be important for European Union countries in the view of the uncertainty and instability of supply of other energy carriers, for example, natural gas and its significant price volatility in the world oil and gas markets, threats of disruption of traditional schemes, and directions of supply.

The next part of this document is organized as follows. Section 2 is devoted to the presentation of the network-matrix formalism of production type model used. The structure of the coal supply model for Ukraine in terms of abstract network of production or import sources and product flow links is described in Section 3. The results of coal flow calculations are also placed here. They demonstrate, in particular, the refutation of the hypothesis of a mandatory decrease in the level of energy security, caused by the forced reduction of the coal mining base. Section 4 covers conclusions on modeling and testing results and a discussion of future model development.

2. Materials and Methods

To obtain the mutually agreed presentation of coal production (mining) objects, as well as a network system of its receipt by import and supply from domestic coal mining enterprises, the authors proposed, in a certain sense, a dual approach to the presentation of such objects. It consists of the application of the economic model of production activities and products proposed by L.V. Kantorovich [70–73] using the concept of "production activity" for a model representation of both technology (a production facility) and product transport links between sources of production, importation, transformation, and consumers of coal products. At the same time, the classical "production activity" [71] is considered here as a connection between the input products of the technology—raw materials and materials, and the output main product of such technology. As a result, a complete coal supply system can be represented by the graph structure of a certain associated supply network and the corresponding equivalent technological matrix of the classical model of production type, according to L.V. Kantorovich. The development of this approach can be found in the works of the authors. A production type model, for example, according to [64,74], can be written in the form of a balance flow model.

In order to express the structure of the flow supply of the fuel supply system into the structure of the data set of the production type model, we have offered to identify its elementary components: the nodes and lines (edges) in the graph of the flow model and the mapping of these elements into the production activities (or their groups) of the production type model. The proposed structural elements of the model of production type are intended to form a general unified system of product balance equations of interconnected networked and non-networked systems of fuel supply. The basic elements of the flow model of the system, intended for the construction of structural elements, which are comprised of the Kantorovich production activities, are the line and the node of the abstract supply system, shown, respectively, in Figures 1 and 2.

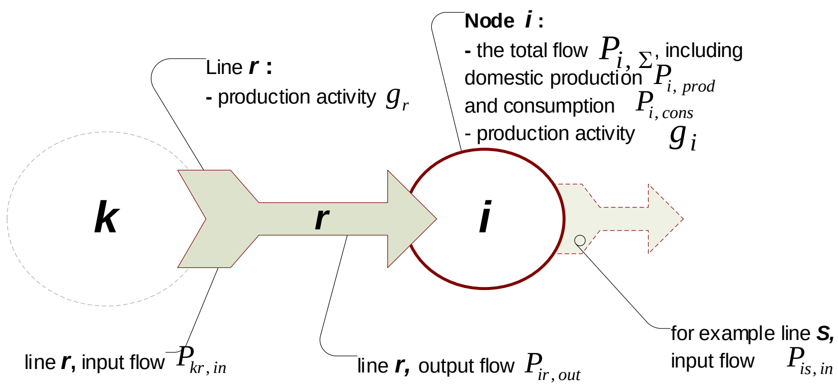

Figure 1. The products of network line [64], (p. 209).

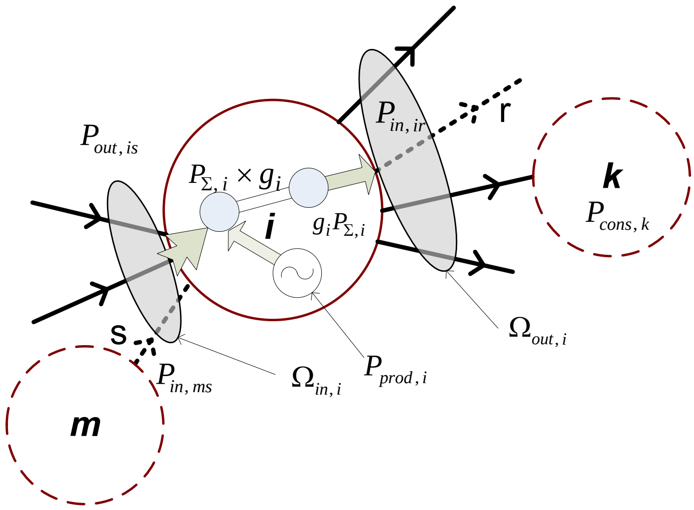

Figure 2. The products of network node [64], (p. 210).

The line ***r***, which receives physical flow from node ***k*** and outputs it to node *i*, is associated with the production activity of the line, in which the model product, the output flow of node k $P_{k,\ out}$ is consumed, the model product of the output flow of the line $P_{ir,\ out}$ is produced, and the ratio of their values is determined by the technological coefficient of input and output of the line g_r. The structural element of the line in the model of the production type is comprised of a single production activity, the model product of which is the output flow of the line.

The structural element of node i with sets of input and output flows $\Omega_{i,\ in}$ and $\Omega_{i,\ out}$, respectively, is formed by an ordered group of production activities, that, in series, (1) produce a variable amount of domestic production of fuel in the node $P_{i,\ prod}$ without consumption of other model products with the appropriate technological coefficient of domestic production $g_{i\ prod}$, (2) produce the input flows of the node $P^{node}_{ir,\ in}$ while consuming the output flows of the lines $P^{line}_{ir,\ out}$ with the proper technological coefficient $g_{ir} = 1$, (3) sum up the amounts of domestic production $P_{i,\ prod}$ and input flows of the node $P^{node}_{ir,\ in}$ and the consumption of this total amount for the production of the total output flow of the node $P_{i\ \Sigma}$ with the technological coefficient of the node g_i.

Equations (1)–(3) represent a generalized material balance.

$$g_{i\ prod} \cdot P_{i,\ prod} + \sum_{r \in \Omega_{i,\ in}} P^{node}_{ir,\ in} - P_{i,\ \Sigma} = 0, \quad i = 1,\ N_{node}\ , \tag{1}$$

$$g_i \cdot P_{i,\ \Sigma} - \sum_{r \in \Omega_{i,\ out}} P^{line}_{kr,\ in} = P_{i,\ cons},\ i = 1,\ N_{node}\ , \tag{2}$$

$$- P^{line}_{ir,\ out}\Big|_{r \in \Omega_{i,\ in}} + g_r\, P^{line}_{kr,\ in}\Big|_{r \in \Omega_{i,\ out}} = 0,\ r = 1,\ N_{line}\ . \tag{3}$$

The system of the balance equations of the node and line products determined in this way represents interconnected networked and non-networked subsystems of fuel product supply in the integrated system of fuel supply. For non-networked systems, the amounts of specific consumption and production of fuel products in the technological links of their production, conversion, and consumption are set by the technological coefficients of nodes $g_{i\ prod}$, g_i and lines g_r, and the balance of amounts is provided by the node material balance condition for the introduced set of products—by the Equations (1) and (2), as well as the abovementioned structure of the system (1)–(3) according to Kantorovich's production activity approach.

The specific definition of the structure of the constructive element of the node with the production activity of production of its total flow and the corresponding technological coefficient allowed us to take into account the interaction of networked and non-networked systems at the level of the conversion amounts of fuel products.

According to the above flow representation of the production system structure, the coal balance equations for different schemes of supply, including the sources of domestic production, technological modernization of mining enterprises, and imports, were formulated.

3. Results and Discussion

3.1. Results

The formal representation of the economic model of the coal supply system in the form of balance equations for the amounts of coal products is determined by the structure of the technological interrelationships of this system, as well as the main goals and tasks of its functioning. The goal of the country's coal supply system is to meet the needs of consumers of various types of coal products through coal mining, its refinement and preparation at the country's enterprises, as well as its import from abroad by sea and railways. The coal demand, in turn, is divided according to its technological destination and is determined by the consumption amount of coking and thermal coal [31,32,75].

From this point of view, the country's coal supply system is a set of technological and economic links for the supply of all types of coal products to the country's economy, both from domestic mining enterprises and imports. The technological processes used to satisfy the demand include mining, refinement, preparation, and transportation of coal from the coal mining enterprise to the final consumer. Import supply consists of the combination of the purchase of the necessary amounts of coal in exporting countries, which are considered as sources of imports, transportation on international trade routes, as well as transportation within a country to enterprises of its final use or transformation [76].

Taking into account these technological processes in the sequence described above for solving the problem of determining the optimal amounts and directions of coal supply is the basis for creating the structure of the balance and optimization model of the country's coal supply, which accounts for the differentiation of coal products by brands and technological destination, as well as the possibility of increasing the competitiveness of the coal industry through the modernization and reconstruction of its enterprises [77,78].

The optimization criterion of the economic model proposed below is the cost of supplying all brands of coal and any technological destination from sources of domestic production and import. Moreover, the country's coal mining enterprises are provided with the possibility to work in one of two operating states: normal production, with the current state of mining equipment, as well as with improved mining technologies and/or total reconstruction (modernization) of the enterprise [77].

The important conditions determining the system of constraints of the proposed model are requirements for:

- The guaranteed demand provision for each of all coal brands;
- Sufficient capacity of import routes, in particular, sea trade ports of the country and its railways;
- Amounts of own production at the enterprise, determined by the variant of its functioning;
- Meeting the energy security requirements according to the quantitative criteria "The share of own sources in the balance of fuel and energy resources of the country" and "The share of fuel imported from one country (company) in its total imported amount" [66].

The model is formulated as follows. It is required to minimize the total costs of coal supply for all brands and any technological destination from sources of domestic production and importation in the possible current and/or technologically improved (modernized) operating state of coal-mining enterprises (1)

$$L = \sum_{k=1}^{N} \sum_{i \in I} \sum_{s \in \{0,\,1\}} \theta_{i,K,s} \cdot C_{i,\,k,s}^{prod} \cdot x_{i,\,k,s}^{prod} + \sum_{i \in I} \sum_{d=1}^{M} C_{i,d}^{imp} \cdot x_{i,d}^{imp} \rightarrow min \quad (4)$$

subjected to the following conditions:

- The consumers' demand is totally provided for each coal brand i

$$\sum_{k=1}^{N}\sum_{s\in\{0,\,1\}} g_{i,k,s}^{prod}\cdot x_{i,k,s}^{prod}\cdot\theta_{i,k,s}+\sum_{d=1}^{M} x_{i,d}^{imp}\geq\ X_{i,\,max}\Big|_{i\in I} \tag{5}$$

- The total amount of imports does not exceed the total throughput capacity of sea trade ports and railways

$$\sum_{i\in I} x_{i,d}^{imp}-X_{tpc,\,max}\leq\ 0 \tag{6}$$

- If coal-mining enterprise ***k*** operates in the state of installed technological equipment with (I) or without (II) reconstruction or modernization (s = 1 and ***s*** = 0, respectively), the total amount of domestic production of coal brand i is determined as follows

$$\sum_{k=1}^{N}\sum_{s\in\{0,1\}} x_{i,\,k,s}^{prod}\cdot\theta_{i,\,k,s}-x_{i}^{prod}\Big|_{i\in I}=0 \tag{7}$$

- The total amount of imported coal of the brand i is determined as a sum of the amounts received from the import source d

$$\sum_{d=1}^{M} x_{i,\,d}^{imp}-x_{i}^{imp}\Big|_{i\in I}=0 \tag{8}$$

- Imbalance between the total amount of domestic production and the threshold amount of total coal supply of the brand i, by the criteria of energy security, is the positive value

$$e_i\geq 0|_{i\in I}, \tag{9}$$

If this imbalance is determined by the legislation regulated ratio γ of domestic production and the total coal supply of the brand i [39]

$$x_{i}^{prod}-\gamma\cdot X_{supply,i}^{\Sigma}\ =e_i\Big|_{i\in I}, \tag{10}$$

and the total coal supply of the brand i is defined as

$$x_{i}^{prod}+x_{i}^{imp}=X_{supply,i}^{\Sigma}, \tag{11}$$

- Imbalance between the amount of imported coal of brand I from each source of import and the threshold amount of this brand's import by the criteria of energy security, is the positive value

$$\Delta_i\geq 0|_{i\in I}, \tag{12}$$

if this imbalance is determined by the legislation regulated ratio Δ_i for the threshold amount of import from each source d [39]

$$x_{i}^{imp}=\lambda\cdot\sum_{d=1}^{M} x_{i,\,d}^{imp}+\Delta_i\Big|_{i\in I} \tag{13}$$

In the model (1)–(13), the coefficients of the target function represent specific values of the cost of coal supplies to the country:

$$C_{i,\,k,s}^{prod}=C_{i,\,k,s\;mining}\cdot\theta_{i,\,k,s}+C_{i,k,\;preparation} \tag{14}$$

$$C_{i,\,d}^{imp} = C_{i,d\ imp} + C_{i,d\ transp\ ,\ ext}, \tag{15}$$

where L is the total cost of coal supply for all brands of coal and sources of domestic production and imports; $C_{i,k,s}^{prod}$ is the coal domestic production specific costs for the brand i at the enterprise k in the variant of operation s within the calculation period; $x_{i,k,s}^{prod}$ is the technologically available maximum amount of domestic production of coal of the brand i from source k in the variant of operation s; $\theta_{I,k,s}$ is the binary variable, determining the variant of operation of enterprise k, which produces coal of the brand i;

$$\theta_{i,k,s} = \begin{cases} 0, \ without\ modernization; \\ 1, \ with\ modernization. \end{cases}$$

$C_{i,d}^{imp}$ is the coal supply specific costs for brand i and source of import d; $x_{i,d}^{imp}$ is the amount of imported coal of the brand i from the source of import d; I is the set of all brands of coal—both thermal and coking coal; $g_{i,k,s}^{prod}$ is technology coefficient of preparation of coal brand i, produced at the enterprise k in the variant of operation s within the calculation period; $X_{i,max}$ is the total demand of consumers for coal of the brand i; N is the number of coal domestic production sources; M is the number of import's sources; $X_{tpc,max}$ is the throughput capacity of the sea import route (total throughput capacity of seaports); x_i^{prod} is the total amount of domestic production of coal of the brand i at all coal mining enterprises; x_i^{imp} is the total amount of coal imports for brand i; e_i is the equalizing variable, determining the value of imbalance caused by the supply of coal of the brand i in case of violation of the conditions of energy safety "Domestic sources share in the total fuel supply to the system"; γ is the value of the indicator of energy security, which determines the share of domestic sources in the balance of fuel and energy resources of the country; $X_{supply,i}^{\Sigma}$ is the total supply of coal brand i into the country; $\gamma_{\min}$, $\gamma_{\max}$ are the minimum and maximum admissible share of domestic production sources in the total fuel consumption of the system, allowed according to the requirements of energy security, respectively; Δ_i is the equalizing variable, determining the amount of imbalance caused by the supply of coal of brand i in case of violation of the energy security requirement on "Part of fuel imports from one country (company) in the total volume of its imports"; λ is the value of the indicator of energy security, determining the share of fuel imports from one country (company) in the total amount of imports; $\lambda_{\min}$, $\lambda_{\max}$ are the minimum and maximum admissible share of the volume of imports from one source, allowed according to the requirements of energy security, respectively; $C_{i,\,k,\,s\ mining}$ is the specific cost of coal production for brand i at enterprise k in variant of operation s;

$$C_{i,\,k,s\ mining}^{\theta} = \begin{cases} C_{i,k}^0, \ without\ modernization; \\ C_{i,k}^1, \ with\ modernization. \end{cases}$$

$C_{i,k\ preparation}$ is the specific cost of coal preparation of the brand i, produced at the enterprise k;

$C_{transp,\,ext}$ is the specific cost of internal coal transportation;

$C_{i,d\ imp}$ is the specific purchase price of coal of the brand i at the source of imports d;

$C_{i,d\ transp,\,ext}$ is the specific cost of external coal transportation of the brand i from the source of import d.

Each Equation of the system (1)–(13) is presented in the model in more detail in terms of a specific network scheme of coal products supply in the form of a set of Equations (1)–(3), which, in turn, are the conditions of the balance of production and transmission amounts, transmission and conversion, transmission, and final consumption. In other words, as balances between node and branch elements of some imaginary network. Such a scheme was developed in this work [76] for the system of supply of thermal coal to the economy of the country, which includes separate subsystems of coal fuel supply by groups: high volatile (D, DG, G brands of coal) and anthracite (A and P brands of coal). These alphabetical designations of coal brands (A, D, DG, G, K, P, PS, Zh) correspond to the Ukrainian coal classification [33].

In each of these subsystems the coal supply is presented by domestic production and import nodes, thus ensuring the competition of supply sources and the influence of the world market on the distribution of coal flows in the system. The sources of supply for each brand of coal have been chosen under the assumption of matching the thermal coal supplied from the exporting countries to the world market [79], and the coal of the domestic production. Considering the differences in the classification of coal [33,34], the comparison of types of imported coal and brands of domestic coal products was carried out according to the indicator of volatiles output.

When modeling the supply of each brand of energy coal there is the possibility of simultaneous inputs by different transportation methods, e.g., by sea, from the countries far afield. Besides the sea route, anthracite and high volatile coal may be transported by railway from the countries nearby, e.g., from Russia and Kazakhstan. These brands may be mined within the territory of Ukraine, which is currently not controlled by the state government, so the scheme of coal supply by brands includes the possibility of input from these territories with their own prices and amount variables.

The structural scheme of supply of the anthracite group, which includes coal of A and P brands, is presented in Figure 3. The supply of the high volatile coal (D, DG, and G brands) is shown in Figure 4.

The sources of anthracite imports from far afield are Vietnam and South Africa (nodes 35, 36, respectively), in view of their significant share in the total volume of trade on the world market [80]. The sources of anthracite supply from nearby areas, except for Russia (node 37), also include the territory of Ukraine, which is currently not controlled by the state government (node 38), because possible schemes of coal supply may include inputs from these territories to the government-controlled part of Ukraine. Russia is the main source of brand P supply to the economy of the country by import (node 39). Other sources of this brand imports were not considered, and the import of this brand from far afield is denoted with dots, as a possible direction of supply. This is caused by the international coal classification features according to which physical and chemical properties, related to brand P, are included in the class of anthracites, without separation to groups in the available statistical data.

The supply of coal of brand D by import is carried out only from the countries nearby—Russia, Kazakhstan, and the territory of Ukraine, which is currently not controlled by the state government (nodes 42, 43, and 51, respectively). The DG brand may be imported from the far afield countries—Australia, Indonesia, the USA (nodes 44, 45, 46, 47, respectively), and nearby countries—Russia, and also from the territory of Ukraine, which is currently not controlled by the state government (nodes 48, 53). The possible sources of brand G imports are Australia, Russia, and the territory of Ukraine, which is currently not controlled by the state government (nodes 40, 41, 52). This structure of imports is proposed as a result of the mentioned coal brands' availability in the markets of these countries.

Coal products received from certain sources of import are accumulated in the nodes, forming the total amount of imports from the countries of far abroad and nearby abroad (nodes 1, 2, 5, 8, 10, 11, and 14 respectively). Coal imported by sea comes to the hub-node, which represents the total throughput capacity of the sea trade ports of the country (node 16). Its amount is further divided to two parts in the next node (node 17). This supply structure was created due to the assumption that some part of the imported coal may be stored at the port for certain period of time. In this part node, two subsystems, namely supplying anthracite and high volatile coal groups, are merged. At the same time, the possibility of mutual substitution of brands is not provided.

The amount of domestic production of brands of anthracite group (nodes 3 and 6, respectively), as well as brands of high volatile group (nodes 9, 12, 15) are subjected to refinement and preparation processes in nodes 19, 22, 25, 28, and 31 to increase their consumer characteristics, finally forming the amount of ready for consumption coal products.

Technology coefficient of preparation [69] for all brands of coal is taken equal to 0,5 [69]. Imported coal is not subjected to refinement and preparation.

Ready-for-consumption coal of domestic production is added to the total import amounts, and the total amounts of coal products (nodes 20, 23, 26, 29, 32) are directed to consumption nodes of anthracite (A+P) (node 33) and high volatile (D+DG+G) (node 34) coal groups, the demand for which was specified as model input data [3,81].

Amounts of imported coal products must meet the requirements of energy security of the state. To check this requirement in the model the amounts of coal supplied from different sources of import and the amount of domestic production must be obtained.

Total imports from the countries of far abroad and nearby abroad for each brand separately are formed in the appropriate nodes (18, 21, 26, 27, 32). These amounts are subjected to the restriction of energy security "The share of domestic sources in the total supply of fuel to the system".

In order to allow for the restriction of energy security "The share of import from one source" for the anthracite coal group, the model includes the total import node (node 49), which represents the summation and distribution structure for brands A and P. The input and output flows of this node are equated to each other by brands. The total import amount formed in this node is further used in proportion with coal flows coming from separate sources of imports separately for A and P brands.

The total amount of import for the high volatile group (D, DG, G) of coal (node 50) is included in the model to allow for the permissible share of each brand of this group in the total imports of this group.

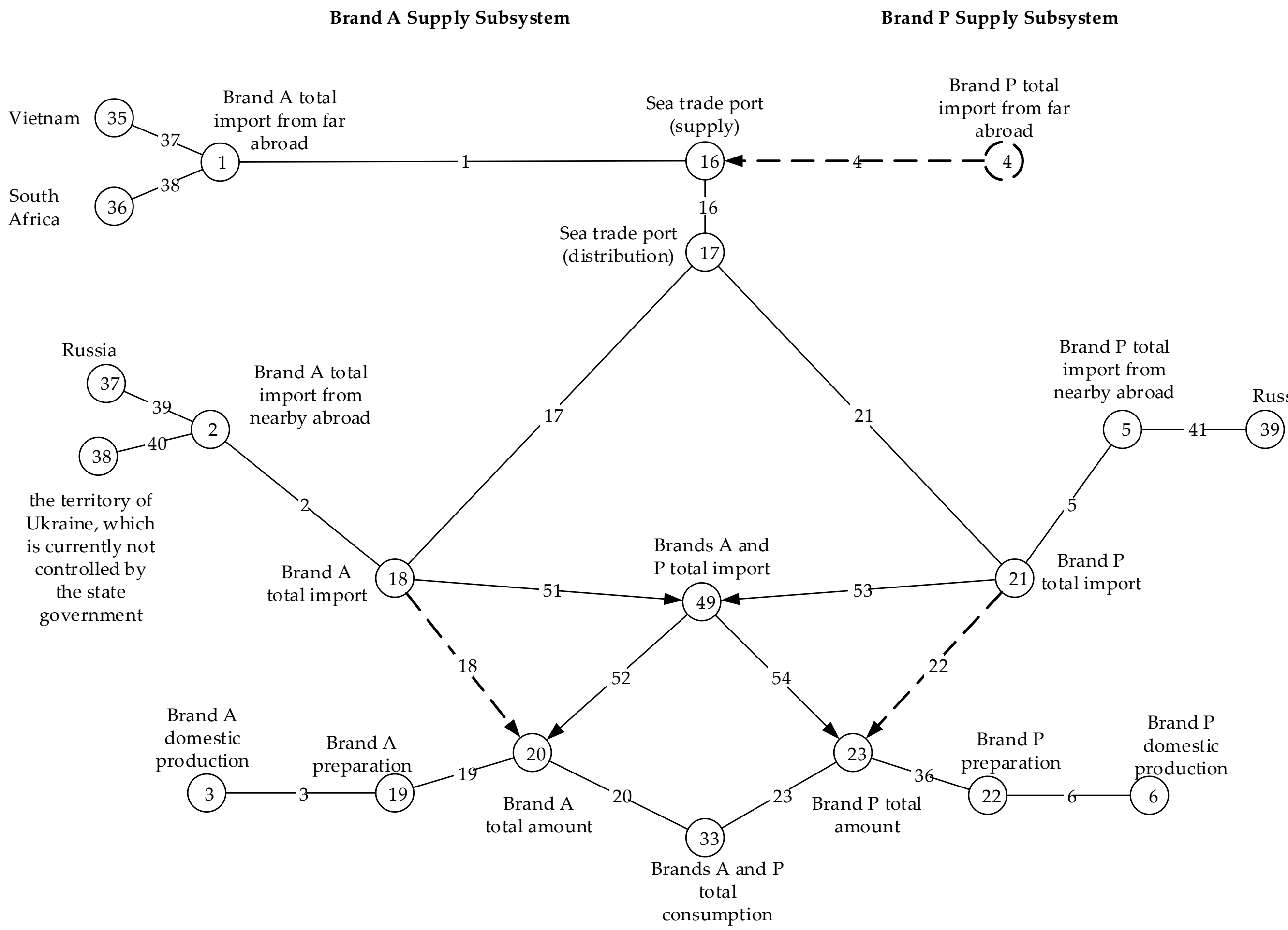

Figure 3. Anthracite supply subsystem [82], (p. 99).

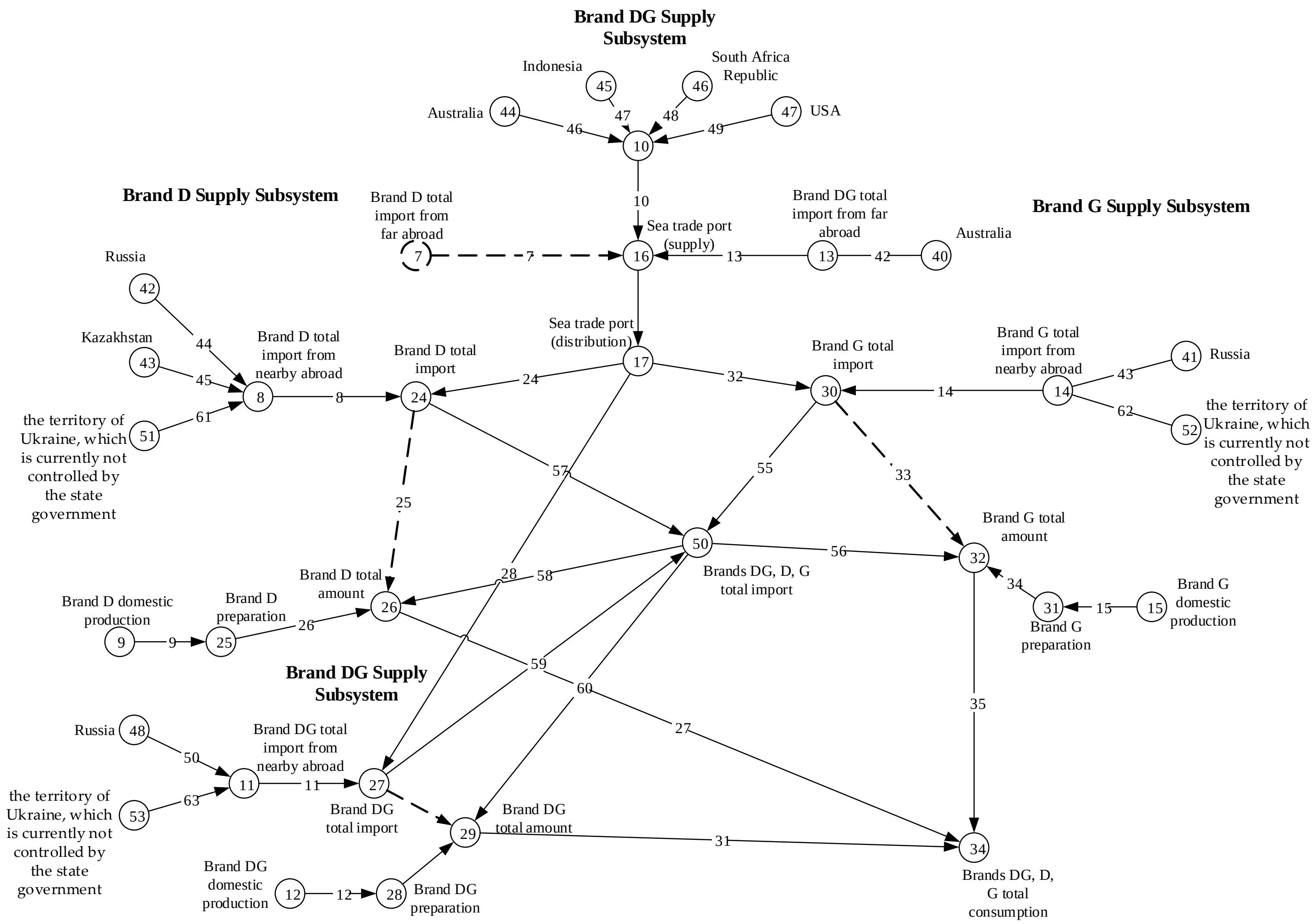

Figure 4. High volatile coal supply subsystem [82] (p. 100). The application of this model to the Ukrainian coal sector implies that only some part of mines can be reconstructed or modernized at the coal mining enterprises located on the controlled territory of the country [83–85]. Other enterprises have practically exhausted reserves, and the implementation of high-cost modernization measures is considered unreasonable for them. Reconstruction of enterprises that are privately owned is beyond the scope of this work considering that the state does not have a significant influence on the owners for investing in their development.

In calculations of coal balances of the country by means of the developed model, the volumes of consumption of different types of coal products were changed according to the possible variants of development of the economic and political state of the state. In particular, the assumption of complete cessation of consumption of anthracite coal group and the transfer of all consumers to the gas group after 2025 were investigated. Among the general economic conditions of modeling, which influenced the limitation of the changed model, the level of its detailing, and data sources for calculations, the following should be named:

- The lack of well-grounded state-level strategies and plans for the development of industrial sectors, which makes it impossible to clearly define the structure and volumes of coal fuel consumption;
- Limited access to long-term plans for reconstruction and development of enterprises that are part of the end use sector;
- The government cannot guarantee the renewal of production of deficit brands of coal, which currently remain on the territory of Ukraine, which is currently not controlled by the state government;
- Reducing the resource capacity of power units of thermal power plants that consume coal fuel, as well as the need for the construction of new or additional reconstruction of existing generating capacities, which will meet the environmental standards of the European legislation and will operate after the end of the life of existing power units;
- Construction of new generating capacities requires the possibility of using project fuel, but the availability of certain brands of coal for the medium and long term remains uncertain.

At the same time, economic efficiency of technological renewal of mines means both energy saving, improvement of ecological conditions [83], and an increase of basic technical and economic indicators: an increase in amounts of coal production, reduction of inputs of material and human resources due to concentration of production, and improvement of quality of coal products, in particular, reduction of their ash content [86]. All these effects of reconstruction and modernization were allowed for in the model by specific cost values.

In particular, in [40,87,88] the authors obtained the estimates for ready-to-use coal product prices for the period up to 2035. These prices were evaluated in the state of implementation of reconstruction and modernization of mining enterprises, and alternatively, in the state without such reconstruction or modernization. Each of the examined enterprises was highly effective in 2015.

The prices used by the model are shown in Table 1.

Table 1. The estimates for ready-to-use coal product prices for the period up to 2035, USD.

Enterprise	Calculated Value					
	2025		2030		2035	
	I	II	I	II	I	II
State enterpise “Pivdennodonbaske №3 by M.S. Surhai“	42.84	50.77	38.49	50.77	37.31	50.77
State enterpise “Krasnoarmiiskvuhillia(G)”	38.49	60.78	35.26	60.78	33.52	60.78
State enterpise “Selydivvuhillia (G)“	35.26	35.26	34.82	35.26	34.82	35.26
State enterpise “Pervomaiskvuhillia (G)“	39.85	103.90	35.26	103.90	35.26	103.90
State enterpise “Lvivvuhillia“	39.43	42.05	38.17	42.05	40.83	47.98
New construction mines	27.59		19.78		14.54	
State enterpise “Mine administration “Pivdennodonbaske №1“	46.75	46.75	44.66	46.75	44.56	46.75
State enterpise “Selydivvuhillia (DG)“	43.67	64.18	41.30	64.18	39.93	64.18
State enterpise “Pervomaiskvuhillia (DG)“	68.79	158.16	59.75	158.16	59.75	158.16

Table 1. *Cont.*

Enterprise	Calculated Value					
	2025		2030		2035	
	I	II	I	II	I	II
Open joint stock company "Lysychanskvuhillia"	40.29	43.02	38.95	43,02	38,95	43,02
State enterpise "Volynvuhillia"	90.50	116.03	90.50	116,03	90,50	116,03
New construction mines	30.71	38.81	27.59	38,81	27,59	38,81
State enterpise "Krasnoarmiiskvuhillia (Zh)"	37.31	46.75	36.24	62,21	35,26	62,21
State enterpise "Toretskvuhillia"	52.04	62.21	52.04	46,75	52,04	46,75
New construction mines	38.49		27.59		27.59	
New construction mines	27.59		21.19		21.19	

The estimated values of coal production cost at private enterprises are shown in Table 2.

Table 2. The estimated values of coal production cost at private enterprises for the period up to 2035, USD.

Enterprise	Calculated Value		
	2025	2030	2035
DTEK Dobropilliavuhillia Limited	21.28	19.94	18.51
Open joint stock company "Pavlohradvuhillia"	25.98	30.12	38.49
Company with additional responsibility "Mine Bilozirska"	38.49	35.26	33.52
New construction mines	27.59	19.78	14.54
Open joint stock company "Pavlohradvuhillia"	12.66	14.85	17.03
New construction mines	30.71	27.59	27.59
Open joint stock company "Krasnolymanske"	50.47	50.47	50.47
Open joint stock company "Ukrvuhlebud"	65.54	65.54	65.54
New construction mines	38.49	27.59	27.59
Private joint stock company "Mining Management Group «Pokrovske»"	17.69	17.69	19.78
New construction mines	27.59	21.19	21.19

Table 3 shows the results of calculations of coal balances carried out on the basis of the developed balance and optimization model of the coal supply of the country with differentiation by brands and technological purposes. The presented above solutions of models (1)–(10) for the amounts of coal supply by brands show that changes in the consumption structure significantly affect the possibility of ensuring the coal balance, in particular, through reconstruction and modernization or increase of imports.

Additionally, the modeling results indicate that the complete termination of anthracite consumption requires the reconstruction and modernization of mines producing high volatile coal groups by 2025, and up to 2035 almost all of the mines currently located in the government-controlled territories will have to be reconstructed to meet the maximum values of their productive capacity.

Under these conditions, imports of high volatile coal will be approximately 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coke coal imports will increase up to approximately 5.46 million tons, 5.151 million tons and 7.377 million tons in 2025, 2030 and 2035, respectively.

Table 3. The results of calculations of coal balances for the period up to 2035.

Indicator	2020	2025	2030	2035
1. Consumption, million tons (input)				
z	2.067	0.0	0.0	0.0
G+DG+D	23.917	32.801	41.6	52.401
Coke coal, total	19.225	18.946	20.726	21.452
2. Supply, million tons (calculated values)				
2.1 Import				
A				
Vietnam	0.62	0.0	0.0	0.0
South Africa Republic	0.62	0.0	0.0	0.0
Russia	0.62	0.0	0.0	0.0
The territory of Ukraine, which is currently not controlled by the state government	0.207	0.0	0.0	0.0
D				
Russia	0.0	0.0	0.0	2.403
Kazakhstan	0.0	0.0	0.0	2,403
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	0.0	2.06
G				
Australia	0.0	0.0	1.313	1.727
Russia	0.0	0.0	1.313	1.727
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	1.125	1.48
DG				
G (for coking)				
Australia	0.447	0.0	0.0	0.0
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	0.0	0.0
PS				
Australia	3.22	1.911	1.803	2.582
Russia	3.22	1.911	1.803	2.582
The territory of Ukraine, which is currently not controlled by the state government	2.76	1.638	1.545	2.213
2.2 Domestic production, million tons				
DG				
State enterpise "Mine administration "Pivdennodonbaske №1"	0.95	0.95	**1.045 ***	0.95
State enterpise "Selidivvuhillia"	0.491	0.491	**1.230**	**1.320**
State enterpise "Pervomaiskvuhillia"	0.075	0.075	**0.535**	**0.570**
State enterpise "Lysychachnskvuhillia"	1.13	1.13	**1.390**	1.13
Open joint stock company "Pavlohradvuhillia"	**14.55**	**14.44**	**10.355**	**7.79**
State enterpise "Volynvuhillia"	0.143	0.143	**0.24**	**0.24**
New construction mines	**0.8**	0.172	**2.85**	**2.85**
G				
State enterpise "Pivdennodonbaske №3 by M.S. Surhai"	0.8	0.8	**1.425**	**1.520**
State enterpise "Selidivvuhillia"	1.71	1.71	1.71	1.71
State enterpise "Pervomaisvuhillia"	0.18	0.18	**0.91**	**1.140**
Open joint stock company "Pavlohradvuhillia"	**1.053**	**3.23**	**2.375**	**1.425**

Table 3. *Cont.*

Indicator	2020	2025	2030	2035
State enterpise "Lvivvuhillia"	1.185	1.185	**1.450**	1.185
State enterpise "Krasnoarmiiskvuhillia"	0.85	**0.915**	**1.4**	**1.9**
New construction mines	0.0	**2.85**	**5.7**	**10.83**
DTEK Dobropilliavuhillia Limited	1.196	**4.895**	**5.605**	**6.55**
Company with additional responsibility "Mine Bilozirska"	0.0	**1.425**	**1.71**	**1.9**
K				
New construction mines	0.0	**2.85**	**4.94**	**4.94**
Private joint stock company "Mining Management Group «Pokrovske»"	**7.2**	**7.2**	**7.2**	**5.7**
Zh				
State enterpise "Krasnoarmiiskvuhillia"	1.4	1.4	1.4	1.4
State enterpise "Toretskvuhillia"	**0.625**	**0.755**	**0.755**	**0.755**
Open joint stock company "Krasnolymanske"	**0.8**	**0.81**	**0.81**	**0.81**
Open joint stock company "Ukrvuhlebud"	0.0	**0.47**	**0.47**	**0.47**
New construction mines	0.0	0.0	0.0	0.0
Total amount of High volatile group preparation	1.196	1.790	2.080	2.620

* here and further in the table the variant of operation of the mine enterprise, which requires reconstruction or modernization, is denoted in bold.

3.2. Discussion

In modeling, the authors used the structure and potential volumes of consumption that existed or were projected to change at the time of the beginning of the military conflict. The current situation in Ukraine creates uncertainty on both the structure of the coal mining industry and the structure of consumption. The advantage of the proposed model is the possibility to take into account different volumes of coal supply and consumption in the sectors of the economy, also taking into account changes in the transport infrastructure.

Obviously, the criterion of efficiency of the functioning of the coal industry used in the article can serve as an indicator of its productivity and efficiency only for specific areas of technical and economic analysis. However, this criterion includes the main costs of the industry in mutually linked technologies of coal production and supply. Some aspects of the coal industry operation are not covered by this criterion. For example, the decision on the termination of operation of low-profitable mines is made on the models of prospective basis. Furthermore, conclusions on the re-equipment of the mine with innovative technologies are usually made on the basis of research in the framework of technological development models. The results of these studies were used in the article mainly to estimate prices for ready-to-use coal products at highly profitable enterprises equipped at the new technology level and mines, which have at this time outdated extraction technologies. In addition, the proposed method of determination of the amounts of production and supply of coal in this paper presents subjection to restrictions of energy security, thus giving a higher level of ensuring the reliability of supply in comparison with the models of technological development, transportation problems, and pure optimization models on the graphs of networks.

As can be seen, the network representation of the supply model allows us to take explicit account of the interrelationships between different technologies and industries, especially highlighting the links between industries in terms of their products. This will make it possible in the future to extend this model to secondary fuels, such as electricity and thermal energy, which will allow the construction of more complete energy balances and constraints on the supply of other fuels and energy.

4. Conclusions

The study of optimal sources and flows of coal products is one of the most important problems of economic and energy security for a country with a developed coal-fuel base, a significant sector of coal-fired thermal energy, that is in a state of military-political conflict and has occupied territories. To solve this problem, the article proposes the structure of the model of coal supply, which takes into account differentiated consumption of almost all brands of coal, restricted supply possibilities from the national resource base and imports, and technological re-equipment of mining enterprises, criteria of energy security.

In our work, we considered coal supplies as a multistream system, differentiated, among other things, by coal brands. Our research shows that already, in 2035, the needs of the economy, including the fuel and energy complex, will exceed the supply of high volatile coal brands from domestic production. In this regard, by 2035, it will be necessary to develop an effective concept of changing the structure of consumption and production of coal fuel, taking into account projects for the development of transport infrastructure.

In this sense, the inherent advantage of the model is the interconnectedness and simultaneous consideration of the volumes of domestic production and transport, as well as technological limitations on these volumes and the limitations caused by military conflict.

Taking into account the occupation while modeling the coal supply is carried out by creating a special structure of the energy coal supply system for the territories under government control, in which the temporarily occupied territories are considered as sources of import with their own amounts and cost indicators of supply and elements of transport infrastructure, as well as including the consumption of enterprises in these territories. The possibility of such modification of the model is ensured by the proposed authors' network representation of the production and supply scheme.

Modeling results demonstrate that imports of high volatile coal will be approximately 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coke coal imports will increase up to approximately 5.46 million tons, 5.151 million tons, and 7.377 million tons in 2025, 2030, and 2035, respectively.

Highly specific conditions of supply of certain groups of energy coal, anthracite and high volatile groups, both from the sources of domestic production and import, are taken into account in the model by individual subsystems of supply, which interact with each other to distribute the number of imports among exporting countries from nearby and far afield while satisfying the throughput capacity of the national transport infrastructure.

Modeling results of the balance of coal products by means of the proposed economic model demonstrate the increase in the level of energy security together with the forced reduction of the coal mining base as a result of the simultaneous decrease in total consumption of all brands of coal, and the availability of high volatile group coal for substitution anthracite before 2025.

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