An Approach to Determining Techno-Economic Characteristics of Aggregated Gas Systems

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Abstract — **The unified gas system of the Russian Federation is a complex, multi-line system that encompasses a host of components and connections. It is virtually impossible to create an exact model that adequately describes all its facilities, hence the need for and relevance of the development of methods for aggregating gas systems. The aggregation of such systems can be conventionally divided into two strands: the aggregation of calculated schemes and the aggregation of techno-economic characteristics of their facilities. This study aims to develop methods for determining the aggregated techno-economic characteristics of the gas system facilities. Methodological approaches to aggregating techno-economic characteristics of gas systems and their facilities were analyzed for both Russia and abroad. The procedure of aggregating the calculated gas scheme is given briefly. The study relies on the methods of graph theory, the method of spreading gas costs and losses between source nodes and arcs of aggregated graph; and the method of determining optimal techno-economic indicators for new gas mains and fields (a combinatorial optimization method based on the maximum net present value, given the payback period of new facilities). The proposed approach to aggregating techno-economic characteristics of gas system facilities was employed to create an information base for multi-level modeling of the development of Russia's gas systems and make calculations for the Unified gas system expansion until 2030.**

***Index Terms*: gas system, aggregation, calculated scheme, gas transmission and gas production companies, techno-economic characteristics.**

I. Introduction

Currently, the gas system (GS) of the Russian Federation includes about thirty natural gas production and transmission companies, most of which are interconnected and constitute the Unified Gas System (UGS). It unites the gas systems of CIS, Eastern and Western Europe, interacts with gas producers in Central Asia and supplies gas to the countries of Northeast Asia. It includes facilities for production (fields), processing (gas processing plants), transmission (line sections of gas mains (GM), compressor stations (CS), gas pumping units (GPU)), underground gas storage facilities (UGS), gas consumers, and others. Solving various problems requires that the characteristics of the facilities be considered to varying degree of detail. This brings about the need for and relevance of the development of methods for aggregating gas systems, in particular, those for determining the aggregated techno-economic characteristics (TEC) of facilities.

The aggregation of gas systems includes the following steps [1]: 1) build an aggregated calculated scheme of a gas system; 2) determine aggregate techno-economic characteristics (TEC) of new and existing gas transmission and gas production companies (GTC and GPC), which also involves demand forecasting for the wholesale natural gas markets; and 3) aggregate in quasi-dynamics by year of the calculation period.

The construction of an aggregated gas system is understood as the transformation of a real-world gas supply scheme into another, simpler one, but corresponding to the

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original one with certain accuracy, while maintaining the required properties of the original scheme in the resulting one [2].

The aggregated techno-economic indicators of new and existing gas transmission and gas production companies are defined as the calculation of TEC of the facilities for the obtained aggregated gas supply scheme. A special emphasis is made on forecasting the demand in the wholesale natural gas markets.

Aggregation in time refers to studies on the future gas system expansion based on forecast data for certain periods of time.

This paper addresses the issue of determining the aggregated TEC of new and existing facilities of the obtained aggregated calculated scheme of a gas system. The approach to aggregating the calculated schemes is briefly described (section III).

II. Analysis of methodological approaches to aggregation of techno-economic characteristics of gas systems and their facilities

The scale and expansion of energy systems, in particular gas systems, brought about the need to aggregate the calculated schemes and the characteristics of their facilities for further study on the optimal path for their development. The method of constructing the aggregated calculated schemes of gas systems is considered in detail in [3].

Several methods are proposed to determine the techno-economic characteristics [1, 4] and aggregate them for the calculated integrated schemes [1, 5–7]. In [4], the structure, composition and definition of TEC are given with the aggregated characteristics often calculated as averaged values. In [7], the focus is on the iterative aggregation according to which the features of the system and statistical data are studied, and then the main indicators of the system are determined and their weight coefficients are set to calculate aggregated characteristics. The use of this method is limited by the impossibility of collecting a huge amount of detailed initial information on the system. In [5, 6], approaches to the aggregation of indicators from the lower hierarchy level to a higher one are shown; and the method of convolutions of particular values of indicators is used.

Although there is no analogue to the Unified gas system of Russia in the world, researchers in other countries also study the development of large-scale gas systems [8–12]. Papers [13, 14] provide a review and comparison of mathematical models developed in different countries. Foreign models consider networks to varying degrees of aggregation (countries, areas, cities) [15]. Such networks require determining aggregated indicators of capacity, but these calculations are not described. In [14], the lack of transparency in obtaining an aggregated network is said to be a common modeling problem.

The main disadvantages of foreign models are: they use outdated data on the costs of natural gas production and on demand for gas; only long-term costs are taken into account; these models assume that the country has a single gas producer, i.e., aggregated source nodes are characterized by the total cost and capacity, some models consider only the full costs for existing capacities, others factor in the capacity expansion by using coefficients; there is no clear demand analysis; perfect competition in the gas production, transmission, and storage is considered.

An important issue for expansion planning of gas systems is the forecasting of gas demand. Various methods are proposed for long-term forecasting based on changes in the parameters of economic development [16, 17], both at the country level and at the regional level, given local characteristics [18]. At the same time, the socio-economic development of the country can be considered according to two scenarios: innovative and energy export-based [16, 17, 19].

The reliability and accuracy of forecasts are very important. The prevailing opinion is that long-term forecasts should be made in a multivariate way, highlighting not two but three main forecast scenarios, i.e., it is necessary to add an inertial scenario to the innovation and energy export-based scenarios (conservative, target, and basic [20]), or consider optimistic, average, and pessimistic ones with an increase in their divergence as the forecast period is extended [17, 21]. Predictive calculations should observe the balance of quantitative estimates (such as the need and its satisfaction). These studies can rely on both expert assessments and appropriate mathematical models.

The demand for natural gas is normally determined by two methods [14, 22, 23]: a) simplified direct counting method and b) analysis of long-term trends in the gas industry development.

The direct counting method is employed to identify aggregated types of products and services produced by individual sectors of the economy and industry, which consume natural gas. The forecast is based on a study of retrospective data. The indicators of product output and gas consumption rates for the considered period are multiplied, or the dynamics of future demand for natural is determined by multiplying the existing volumes of consumption and the established indices for the estimated periods. The direct counting method is the more reliable the closer the period under consideration.

The method of analyzing long-term trends in the gas industry development is aimed at analyzing the solutions obtained from the model of the national energy sector, the possible quantitative indications of the objective trends that characterize the relationship between the development of the gas industry and that of the country's economy. First, quantitative manifestations of new trends are determined, and then possible hypothesized quantitative manifestations of such trends in the period under review are evaluated.

Some researchers, when determining the demand for gas by country, proceed from information on the area and population of the country, and use specific coefficients of gas consumption per capita [15].

An analysis of the scientific and practical experience available in the world shows that the problem of aggregating gas systems has not been sufficiently studied and systematized. The poorly developed areas of the aggregation of techno-economic indicators of system facilities are:

– the aggregation of several fields into one source node and gas consumers into one consumer node does not factor in the throughput capacity of gas mains between them;

– the coefficients of auxiliary gas consumption and gas leakages are not taken into account for gas production and transmission companies;

– the economic indicators of the system, such as the costs of gas production at source nodes and gas transmission along the arcs of the graph are not considered, which does not allow determining the gas price at the consumer's in the future.

– the gas prices for the consumer in Russia are set according to price zones, which does not always reflect the real costs of gas companies.

The scientific novelty of this study is as follows: the methods have been developed to determine the aggregated techno-economic characteristics of gas sources and gas mains, which are used in building the information base, namely the method of spreading costs and losses between source nodes and arcs of the aggregated graph, and the optimization method based on the maximum net present value (NPV), given the payback period of the facilities.

III. Aggregation of the Calculated Gas Supply Scheme

Gas system is considered at three levels: 1) gas mains, fields, underground gas storages; 2) gas transmission and gas production companies; 3) Unified gas system of the Russian Federation. When solving the problems of optimal expansion for gas systems, we first address techno-economic characteristics of their components of a lower level (gas mains, fields), then these data are used to determine the characteristics of the GTC and GPC, after which the entire Unified gas system is considered, where the optimal flows, directions and cost of gas transmission are determined.

The gas system is represented as a directed graph and is considered as a set of three subsystems: gas sources, gas main networks, and consumers. The initial data for these systems are:

– ***for the sources***: maximum annual gas production at all fields and for gas production companies in total, operating costs and proportion of gas losses at the GPC. The information used is from the Main Directorate of Natural Resources of the Ministry of Natural Resources of the Russian Federation and the Service of JSC Gazprom;

– ***for the UGS gas mains***: diameters, number of lines, lengths, connection points of all compressor stations, operating costs and the proportion of gas losses at the GTC (auxiliary gas consumption and gas leaks). The UGS maps and collected statistical information used are provided by the JSC Gazprom;

– ***for the consumer***: projections of future demand for gas for constituent entities of the Russian Federation, various industries, and gas exporting countries, which are obtained using the models of the energy sector of the Russian Federation, as well as the data from the General Development Scheme for the gas industry and other sectors of the economy.

Using the developed algorithm [3], shown in Table 1, we obtain an aggregated calculated scheme for the UGS, brought to the level of the constituent entities of the Russian Federation. As a result, each entity is represented by one consumer node and one source node, if the entity has gas fields. The network of gas mains between the nodes is represented by arcs in a single-line representation.

As seen in Table 1, the resulting values for demand for gas (step 2), gas production (step 3), throughput capacity

Table 1. Algorithm for aggregating a detailed gas supply scheme

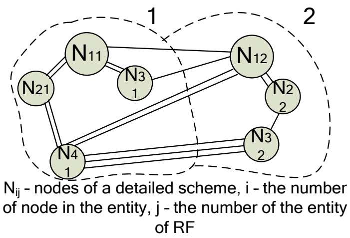
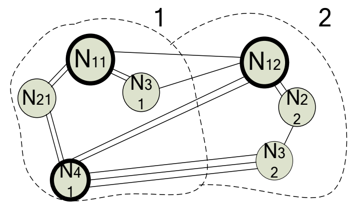
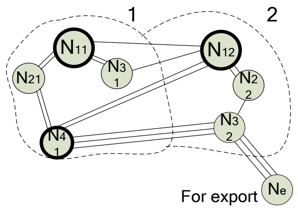
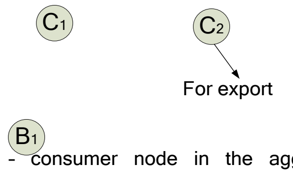
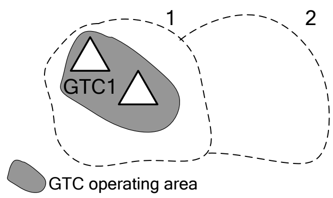
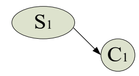
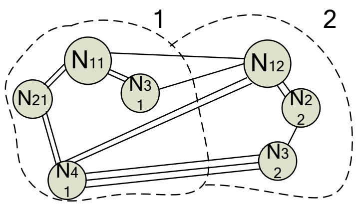
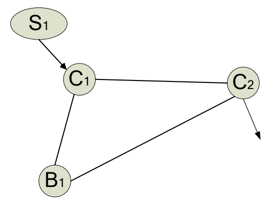
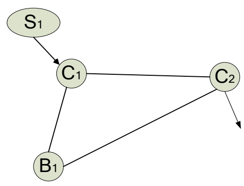
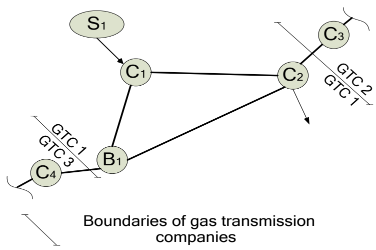
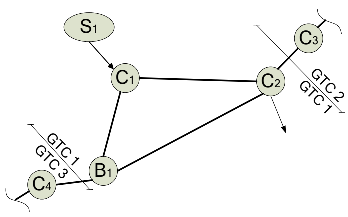
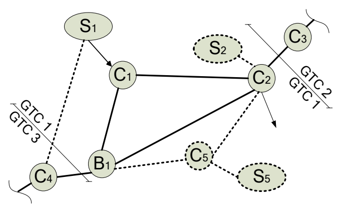
	Actions	Original scheme	Obtained scheme
1. Identify adjacent nodes	1. Identify branching nodes in the scheme.		
2. Identify aggregated consumer nodes and branching nodes	1. Identify the maximum demand nodes. 2. Match consumer nodes with adjacent branching nodes. 3. Assign the volume of export deliveries from entity to consumer node. 4. Calculate aggregated demand. 5. Select main branching nodes.		 C_i - consumer node in the aggregated scheme B_i - branching node in the aggregated scheme
3. Aggregate source nodes by GPC	1. Identify source node. 2. Determine aggregated production.		 S_i – source node in the aggregated scheme
4. Aggregate gas mains	1. Represent multi-line gas mains by single-line arcs. 2. Determine the throughput capacity of aggregated arcs. 3. Determine the length of arcs.		
5. Glue the obtained aggregated schemes for each GTC into one	1. Connect aggregated schemes along the GTC operating boundaries.		
6. Build a redundant scheme	1. Add projects of new gas pipelines and new fields prepared for the development, and new consumers to the scheme.		

Table 2. Methods for determining the aggregated technical and economic characteristics of the UGS of the Russian Federation

Facilities	Existing gas transmission companies	Existing gas production companies	New gas mains	New fields
Methods	Method of spreading costs and losses		Combinatorial optimization method based on the maximum NPV in terms of the payback period	
Main techno-economic indicators to be determined	1. Costs of gas transmission through pipes of different diameters 2. The cost of gas transmission along the arc 3. Specific costs for transporting 1 000 cubic meters of gas along the arc 4. Coefficients of auxiliary gas consumption and leakage 5. Coefficient of reduction in arc throughput capacity	1. Specific costs of GPC 2. Coefficients of auxiliary gas consumption and leakage 3. Coefficient of reduction in gas production due to losses	1. The number of compressor stations, length of pipes between them 2. Gas pumping units and their sizes 3. Capital investment in and operating costs of gas mains 4. Net present value (NPV) 5. Payback period	1. Production capacity of the field by year 2. Forecast price set 3. Net profit 4. Discount factor 5. Profitability 6. Cash flow 7. NPV 8. Payback period

supply scheme are determined by summing the corresponding values of the detailed scheme, provided they are equal in the original and aggregated schemes.

IV. MODELING OF AGGREGATED TEC OF GAS SYSTEMS AND THEIR FACILITIES

Modeling of aggregated TEC of existing gas transmission companies. Gas transmission companies (GTCs) transport natural gas through the gas pipeline system. Each GTC has its own clear boundaries, provides a certain territory with gas and export gas to other areas. For each existing GTC, the operating costs of the company (the cost of gas transmission), the length of the gas pipeline, the number of lines and diameters, the auxiliary gas consumption (aux) and losses are established based on the standard reference sources.

Table 2 presents the methods for aggregating the main TECs of gas transmission and gas production companies, both existing and new ones.

The prices for gas transportation along the arcs are determined based on the operating costs and the total length of the GTC gas mains, and their diameters. Operating costs, given the coefficients, are spread over the entire total length of gas pipelines. It is known that the operating costs associated with the gas transmission through gas pipelines of large diameters are less than those for the transmission of the same gas volumes through gas pipelines of smaller diameters. Quantitatively, this fact can be determined through the cost overrun factors (y_k) for the transmission of 1 000 m^3 of gas through gas pipelines of various diameters in terms of a gas pipeline with a large pipe diameter taken as a base (normally 1 420 mm), Table 3 [1].

The operating costs of the GTC are given as a table representing the cost estimate.

The need for financial (cash) resources of the GTC given in the table reflects the cost of natural gas transportation for this company. Gas transmission company establishes a rate of return, which stimulates the expanded production of the company and provides personnel bonuses.

The GTC costs can be considered basic costs ($D(B)_{GTC}$) formed at a certain point in time t_B. Basic costs remain unchanged throughout the considered period.

Table 3. Cost overrun factor (γ_k)

Pipeline diameter, mm	Factor, γ_k
1 420	1.0
1 220	1.07
1 020	1.15
820	1.65
720	2.45
529	3.45
Others	4.5

Table 4. Nominal throughput capacities of main gas pipelines of different diameters

Diameters of pipes, mm	1 420	1 220	1 020	820	720	529	426	377	325
Throughput capacity, billion m^3/year	30.0	18.5	9.0	6.2	4.2	2.0	1.0	0.6	0.4

Forecast costs ($D(t)_{GTC}$) at the end of the t-th forecasting step are calculated by the expression [24]:

$$D(t)_{GTC} = D(B)_{GTC} \cdot J(t, t_0),$$

where $J(t, t_0)$ is an index of change in the costs at the end of the t-th step with respect to the initial moment of calculation (t_0).

Transportation rates for 1 000 m^3 of gas along the arcs of the calculated graph (c_{ij}) are determined as follows:

$$c_{ij} = \frac{T_{ij}}{Q_{ij}},$$

where T_{ij} is the cost (forecast costs) of gas transportation by link ij; Q_{ij} is the nominal throughput capacity of link ij, which is found as a sum of throughput capacities of gas main lines aggregated in arc ij.

Cost of transmission along arc ij is calculated as follows:

$$T_{ij} = \sum_{k=1}^{n} \Theta_k L_k,$$

where L_k is the length of gas main with diameter d_k in one-line calculus; Θ_k is price (rate) of gas transmission by the gas pipeline with diameter d_k at a distance of 1 km,

$$\Theta_k = \Theta_k \cdot \gamma_k.$$

Here $k = \overline{1, K}$; K is the number of options for gas pipeline diameters, for example, $d_1 = 1\ 420$, $d_2 = 1\ 220$, $d_3 = 1\ 020$, …

Tariff for gas transmission through the gas pipeline of the first diameter ($d_1 = 1\ 420$ mm) is calculated from the expression:

$$\Theta_1 = \frac{D_{GTC}}{\sum_{k=1}^{K} \gamma_k \cdot L_k},$$

where D_{GTC} is the financial requirement of the company, which is taken from the cost estimate table.

Each arc of the aggregated graph displays one or several existing MGs of corresponding diameters. The throughput capacity of this arc (upper limit) is determined as the sum of the nominal throughput capacities of the mentioned gas pipelines. Approximately, their values for MGs of various diameters at a pressure of 7.5 MPa are given in Table 4.

Each edge (arc) of the calculated graph of a gas transmission company displays the lengths of gas mains of corresponding diameters, which are included in this arc. The sum of the gas main lengths for all edges corresponds to the length of the gas pipelines belonging to this company.

Auxiliary gas consumption of main gas pipelines for a year is usually determined based on the number of GPUs in operation, the number of their operating hours per year and their technical characteristics (GPU types, unit capacity, specific fuel consumed by GPUs, efficiency, and others). We propose a simplified method for determining the auxiliary gas consumption, based on the share (percentage) of gas consumed for pumping gas through gas pipelines of gas transmission companies (taken from the reference books of the gas industry for recent years). An analysis of these shares shows a certain stability of their values in dynamics.

The coefficients showing the decrease in yearly gas supply volumes due to the auxiliary gas consumption on the edges of the calculated graph of the gas transmission company are found from the expression:

$$\alpha_{aux_{ij}} = \frac{0.01 \cdot P_{aux}^{GM}}{L} L_{ij},$$

where L is a length of gas pipelines in single-line calculus of the gas transmission company, km; P_{aux}^{GM} *is* the share of gas assumed for calculations, L_{ij} is the lengths of gas pipelines of arc ij on the calculated graph of the gas transmission company, km.

The level of gas losses to the atmosphere at gas industry entities can be divided into background, technologically inevitable, and emergency ones. According to official statistics, in total, these losses range from 3.3% to 7.2% of the annual gas production [1].

The coefficients showing the decrease in yearly gas supply volumes due to gas leakage into the atmosphere on the edges of the calculated graph of the gas transmission company are determined by the following expression:

$$\alpha_{loss_{ij}} = \frac{0.01 \cdot P_{loss}^{GM}}{L} L_{ij},$$

where P_{loss}^{GM} is the gas share of the considered GTC, %.

The coefficient, which simultaneously takes into account the decrease in gas supply volumes per year in a gas transmission company due to auxiliary gas consumption and losses, is as follows:

$$\alpha_{ij} = \alpha_{aux_{ij}} + \alpha_{loss_{ij}} .$$

Modeling of aggregated techno-economic characteristics of the existing gas production companies (GPCs). Based on the reference literature, the state of the raw material base at the fields of the gas-bearing region is determined. The operating costs of a gas production company are given in the form of a table presenting the cost estimate.

The cost estimate is the basic cost of extracting natural gas at a given point in time t_B. The basic costs of a gas production company remain unchanged throughout the entire considered period.

Forecast costs ($D(t)_{GPC}$) at the end of the t-th prediction steps are determined as follows:

$$D(t)_{GPC} = D(B)_{GPC} \cdot J(t, t_0).$$

Here $J(t, t_0)$ is an index of change in the costs at the end of the t-th step with respect to the initial instant of calculation (t_0) (similarly to GTC).

Costs reflect the gas production cost and the profit required for expanded production. Self-financing price (C_{GPC}) is calculated as follows

$$C_{GPC} = \frac{D_{GPC}}{Q_{GPC}},$$

where D_{GPC} is the need of the GPC for financial resources according to cost estimate; Q_{GPC} is the forecast "upper" volume of gas production by the GPC.

The coefficient that factors in auxiliary gas consumption is found from the expression

$$\alpha_{aux}^{GPC} = \frac{P_{aux}^{GPC}}{100}.$$

Here P_{aux}^{GPC} is the share of auxiliary gas consumption of GPC, %.

The coefficient showing the decrease in gas supply volumes per year due to emergency gas leakages is determined from the expression:

$$\alpha_{loss}^{GPC} = \frac{P_{loss}^{GPC}}{100}.$$

Here P_{loss}^{GPC} is a share of gas leakages assumed for GPC, %.

Coefficient that simultaneously takes into account the decrease in yearly gas production volumes at the GPC due to the auxiliary gas consumption and losses (Q_{GPC}) is found as follows

$$\alpha_{GPC} = \alpha_{aux}^{GPC} + \alpha_{loss}^{GPC} .$$

Modeling of techno-economic characteristics of new gas transmission companies (GTCs). The development of new gas transmission projects requires an assessment of their economic and social implications, as well as the costs associated with social activities and environmental protection. The costs and efficiency of the project are assessed for the calculation period. The assessment of the project cost-effectiveness involves the coordination of multi-temporal indicators by reducing (discounting) them to the values in the initial period. The reduction of the costs, results and effects at different times is based on the discount rate (E), which is equal to the rate of return on capital acceptable to the investor.

Comparison of various projects and selection of the best one is based on the following indicators.

1. *Net present value (NPV)*. It is determined as the sum of current effects for the entire calculation period, which is reduced to the initial step, or as an excess of integral results over integral costs [24].

$$NPV = \sum_{t=0}^{T} \left(R_t - З_t\right) \frac{1}{\left(1+E\right)^t},$$

R_t is results achieved at the t-th step of calculation; $З_t$ is costs incurred at the same step; T is calculation horizon.

If the NPV of the project is positive, the project is efficient (at a given discount rate). The higher the NPV, the more economically efficient the project is.

2. *Profitability index (PI)*. PI is the ratio of the sum of effects reduced to capital investments (K)

$$PI = \frac{1}{K} \sum_{t=0}^{T} \left(R_t - З_t^*\right) \frac{1}{\left(1+E\right)^t},$$

where $З_t^*$ is the costs at the t-th step provided they exclude capital investment.

If the NPV value is positive, then $PI > 1$ and vice versa. Thus, if $PI > 1$, the project is economically viable.

3. *Internal rate of return (IRR)*. IRR is a discount rate (E_{aux}), at which the value of the reduced effects is equal to the reduced capital investment, and can be obtained by solving the equation:

$$\sum_{t=0}^{T} \frac{R_t - З_t^*}{\left(1+E_{IRR}\right)^t} = \sum_{t=0}^{T} \frac{K}{\left(1+E_{IRR}\right)^t}.$$

The obtained value of IRR is compared with the rate of return set by the investor. If the value of IRR is greater than the rate of return set by the investor, investment in this project will be justified.

4. *Payback period.* This is the minimum time interval (from the beginning of the project), beyond which the integral effect becomes non-negative.

A simplified algorithm for creating and developing a new gas transmission system and determining its techno-economic characteristics, as well as the wholesale gas sales price, is as follows.

Gas main is considered as a separate newly commissioned facility of the gas system, without connection with the gas source and consumers, and may contain one or more pipes and compressor stations with the same type of gas pumping units. Hydraulic calculations for placing compressor stations and calculations for choosing the number of standby operating GPUs are carried out for normal (standard) gas transmission conditions [1]. The possibility of redundancy due to the storage capacity of the end sections of the main pipelines and due to the forced operation of the gas compressor units within the technical limits is not taken into account.

The calculated scheme of a multi-line gas main is a chain of series-connected links, i.e., sections of pipelines and compressor stations, for which, capital investments and annual costs are determined depending on different combinations of equipment.

The horizon for considering the flow of funds into the gas transmission system is the service life of this system, as a rule, it is 30–35 years, while the payback period is about 7 years.

The gas transmission system is considered as a system of pipelines without gas takeoffs from the pipeline on the route with set annual production capacity Q_G and gas pipeline length L. A list of possible diameters of pipes to be used for the construction of the main gas pipeline, the number of lines and a list of standard sizes of gas pumping units to be installed at the compressor stations are also set.

Specific capital costs for the linear part of the gas main (k_{Li}) covering the costs of the territory preparation, steel pipes and their transportation, auxiliary equipment, construction and installation works, are chosen as the average of the values of specific capital costs for flat-hilly, flooded, permafrost soil and mountain areas with high seismicity (magnitude of earthquakes up to 8). Specific annual investments in the construction of industrial and auxiliary facilities (k_{aux}) include the costs of gas measuring stations, houses of linemen, control stations, landing sites, power supply, electrochemical protection, roads, communications, and remote control. Specific annual investments in housing and social facilities consist of the costs of housing construction, given the housing cost ($k_{h.c.}$). The total specific annual investments in the linear part of the gas pipeline depending on diameter are equal to the sum of the above values:

$$K_{link\ i} = k_{Li} + k_{aux} + k_{h.c.}.$$

Specific annual operating costs of the linear part represent the costs of labor, allocations for social needs, depreciation, and other costs (S_{Li}).

Specific annual investments in compressor stations equipped with various types of gas pumping units include the cost of preparatory work, compressor shop, gas treatment, purification and cooling units, technological networks, auxiliary facilities, off-site facilities, gas pipelines, and flow lines ($k_{cs\ j}$).

Specific annual operating costs for the compressor station, which depend on the installed capacity and type of GPU, include tangible costs, costs of gas for auxiliaries, labor costs, allocations for social needs, depreciation, and other costs (S_j).

Specific annual operating costs for the compressor station, which do not depend on the installed capacity, are determined by the share of the annual costs for the compressor station, as per the size of gas pumping units ($S_{n\ j}$).

The net present value of the gas pipeline designed and the payback period are determined by the cash flow algorithm (simplified business plan) [25]:

Consider various options of standard sizes of GPU and pipes. Select the calculation in which the NPV has the highest value. Compare the payback period of the project of this option with the payback period norm. If the payback period is less than or equal to the norm, then the calculation is completed. If the payback period is longer than the norm, then the accepted gas sale price is increased by some given value. The process of iterative calculations ends if the payback period is less than or equal to the norm of the payback period.

Modeling of techno-economic characteristics of new gas production companies (GPCs). In the context of insufficient information on newly discovered fields, we propose the following simplified algorithm for determining the aggregated techno-economic characteristics of the GPC.

1. Find similar existing projects based on exploration data and a preliminary geological assessment of the field. By analogy with these projects, estimate gas production

Table 5. Gas consumption by constituent entities of the Russian Federation and gas export to FSU and non-FSU countries, billion m^3

		2020			2025			2030		
No	Node	Internal	Export	Total	Internal	Export	Total	Internal	Export	Total
1	Belgorod	8.6	0	8.6	11.2	0	11.2	14.5	0	14.5
2	Bryansk	3.6	0	3.6	4.1	0	4.1	4.7	0	4.7
3	Gavrilov–Yam	18.8	0	18.8	20.5	0	20.5	22.4	0	22.4
4	Novopskov	8.8	11	19.8	12.4	9	21.4	17.5	7	24.5
5	Kaluga	3.1	0	3.1	4.2	0	4.2	5.7	0	5.7
6	Kursk	3.3	40	43.3	3.6	25	28.6	3.9	25	28.9
7	Dace	6.4	0	6.4	6.4	0	6.4	6.4	0	6.4
8	Moscow	50.0	0	50.0	52.3	0	52.3	54.7	0	54.7
…	…	…	…	…	…	…	…	…	…	…

Table 6. Calculated techno-economic indicators of gas transmission links for the aggregated gas supply scheme

			2020		2025		2030	
Arc	α	Q max	Q, bn.m^3	C, USD/1000 m^3	Q, bn.m^3	C, USD/1000 m^3	Q, bn.m^3	C, USD/1000 m^3
Kursk–Belgorod	0.999	13.2	8.61	1.1	11.21	1.2	13.20	1.3
Kursk–Orel	0.999	13.0	6.41	2.0	7.11	2.2	8.01	2.3
Yelets–Tula	0.997	54.0	9.53	1.2	9.93	1.3	10.43	1.5
Yelets–Kursk	0.998	130.0	58.44	0.3	47.02	0.3	50.21	0.4
Yelets–Novopskov	0.998	48.2	48.20	2.2	48.20	2.5	48.20	2.6
…	…	…	…	…	…	…	…	…

(Q), capital investments (K), fixed assets (FA) and costs, given that costs rise every year due to inflation.

2. Build a schedule of production by year, depending on the maximum possible annual demand for gas of the field. Production goes up for the first three to five years, then the maximum capacity (approximately 10 years) is used, then production declines. Determine production capacity by year (Q_t).
3. Calculate the forecast price (P_t) of gas at the end of the t-th year of calculation by the formula [24]: $P_t = C_0 \cdot J_t$, where J_t is the index of changes in the prices of products or resources of the corresponding group at the end of the t-th step with respect to the initial instant of calculation (at which prices are known). Set the value of J_t according to the projections of the Russian economy.
4. Determine revenue for each year: $R_t = Q_t \cdot P_t$; costs (C_t) are set in % of FA; gas prime cost: $S_t = C_t / Q_t$; balance sheet profit: $BP_t = R_t - C_t$; income tax $IT_t = n$; BP_t (n is the rate of tax on taxable profit); net profit $NP_t = BP_t - IT_t$; discount factor: $a_t = 1/(1+E_t)^t$ (E_t is the discount rate); attracted investments $AI_t = I_t - S_d t - NP_t$, if $AI_t < 0$, then the attracted investments are assumed to be equal to 0; product profitability: $P_t = (R_t - C_t)/C_t$.
   Investments over the periods can be characterized by both revenues and costs. If for the period under review, revenue exceeds costs, this means the net revenue or positive cash flows; if costs exceed revenues, then there are net costs or cash outflows. Some cash flows are subject to taxation, they should be calculated after the tax assessment.
5. Determine cash flow ($CF_t = NP_t + C_{d\,t} - I_t$) and net present value ($NPV_t = CF_t \cdot a_t$).
6. Calculate loan payments if $CF_t > 0$.
7. Define the payback period as the time required for the revenues from an investment project to become equal to the initial investment in this project. If the cash flow from the investment project is expected to be constant over several years, the payback period can be found by dividing the initial investment by the expected annual revenues. If the expected flow of earnings varies from year to year, then the payback period can be determined by summing the expected revenues over the years until

Table 7. Addition of new capacities in the gas transmission system by year

Initial node	Final node	Capacity, billion m^3		
		2020	2025	2030
Novopskov	Rostov-on-Don	30		
Syktyvkar	Gryazovets	50		
Gryazovets	St. Petersburg	30		
Gryazovets	Torzhok	30		
Rostov-on-Don	Maykop	30	60	
Ukhta	Pomary	60		120
Yamal	Ukhta		140	90
…	…	…	…	…

their total equals the initial investment. To determine the payback period, the number of periods (years) in which $NPV < 0$ is calculated.

8. Compare the payback period of the project with its norm equal to 7 years. Complete calculations if the payback period becomes less than or equal to this norm. Otherwise, set a higher value of the price P_t, and repeat the calculation until this condition is met.

V. Results of Research on the UGS Expansion until 2030 Based on the Proposed Approach

Based on the approach proposed, a redundant aggregated scheme was built and an information base of techno-economic indices of unified gas system facilities was created. The calculated indicators for the aggregated scheme, for example, gas consumption at consumer nodes, arc capacities and loss factors are given in Tables 5 and 6 (columns 2, 3), respectively.

The possibilities for the development of gas systems in Russia, given the internal needs of the markets and specified export deliveries to the FSU and non-FSU countries were assessed using a network flow model. The quasi-dynamics of the gas system development in European Russia together with eastern part of the gas industry was calculated for 2025 and 2030.

The calculation results for existing and new gas transmission systems of the aggregated scheme are shown in Table 6. Their analysis suggests the need for the construction of new gas pipelines, which are presented in Table 7.

Table 8 presents the results of gas flow calculations for the aggregated Unified gas system for 2025 and 2030,

Table 8. Balance of the main indicators of the gas industry development, billion m^3

Item	Years	
	2025	2030
Gas consumption in Russia, total:	507 – 593	517 – 641
Entity 1	120 – 140	120 – 146
Entity 2	124 – 150	129 – 170
…	…	…
Export, total:	270 – 395	285 – 430
Non-FSU countries	230 – 320	230 – 350
FSU countries	40 – 75	55 – 80
Gas consumption for process needs of gas mains	58 – 73	58 – 75
Total gas for distribution	835 – 1061	860 – 1146
Gas production in Russia, total	799 – 1049	827 – 1068
Source 1	450 – 490	350 – 450
Source 2	230 – 300	330 – 420
…	…	…
Gas supply from Central Asia	35 – 40	30 – 40
Gas resources, total	835 – 1061	860 – 1146

corresponding to the average scenario of economic development.

VI. Conclusion

1. The paper has briefly presented an approach to aggregating a real-world gas system, i.e., presenting it in the form of a simpler calculated scheme characterized by a smaller number of nodes and connections.

The proposed approach makes it possible to take into account small fields, independent gas producers, and minor gas mains both between the entities and within them.

2. Methods for aggregating the techno-economic characteristics of both existing and new gas system facilities have been developed: the method of spreading costs and losses between the arcs and source nodes of the aggregated graph is used for existing GTCs and GPCs; a combinatorial optimization method based on the maximum NPV, given the payback period of the facilities is employed for new GTCs and GPCs.

The proposed procedure for aggregating techno-economic indices makes it possible to factor in the capacity of small gas mains between several source nodes or consumers of a detailed scheme, and coefficients of auxiliary gas consumption and leakage for GPCs and GTCs.

3. The proposed approach has been applied to aggregate Russia's gas system scheme, create an information base for multi-level modeling of the gas system development in Russia until 2030, analyze the current state of the gas industry of the Russian Federation (gas production, gas transmission, and demand for gas in various industries); determine the techno-economic characteristics of its facilities; and identify the prospects for the expansion of gas supply to the constituent entities of the Russian Federation.

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