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Работа выполнена в рамках программы получения стипендии Президента Российской Федерации для молодых ученых и аспирантов, осуществляющих перспективные исследования и разработки по приоритетным направлениям модернизации экономики России (СП-4481.2021.1)

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Consumer gas supply on the basis of liquefied natural gas

Abstract. Determination of the optimal alternative to natural gas is presented in the form of using liquefied natural (LNG) and liquefied hydrocarbon gases (LPG) for energy supply to various categories of consumers. A preliminary assessment of the cost-effectiveness of using liquefied natural gas as a substitute for LPG is in favors of the latter as an ecologically clean and competitive energy carrier. This study explores ways to optimally deliver natural gas to consumers and considers options for pipeline and road transport. To evaluate the results of gas consumption, a hydraulic calculation program was developed and used with optimization of pressure drops across sections of the gas distribution and gas consumption network. A method is proposed for assessing the economical delivery of gas to consumers, based on solving a logistical and mathematical problem and allowing to determine the optimal radius of LNG delivery to various categories of consumers, depending on the annual gas consumption, the distance of consumers from the gas supply strong point — the source of gas supply, which are: a gas distribution station — in the pipeline transport version and an LNG production plant — in the version of LNG delivery by road cryogenic tanks. As an example, an algorithm for determining the location of an LNG plant based on the coordinates of non-gasified cities of the Kirov Region was considered. As a result of solving the logistics problem of the center of mass, the total annual profit from the optimal location of the natural gas liquefaction plant amounted to 524.28 million rubles. The results of the study on the use of alternative sources of gas supply show high possibilities of using LNG for all domestic and industrial needs of various categories of consumers mutually remote from the main gas pipeline. In addition, the use of the developed program for hydraulic calculation with optimization of pressure drops makes it possible to obtain savings in material and financial resources for the option of a subsequent long-term transfer of consumers from LNG to network natural gas.

Keywords: liquefied natural gas; natural gas; gas supply; cryogenic tank; energy efficiency; transportation; energy conservation; numerical methods; cost effectiveness; optimization

Introduction

Natural gas is one of the main components of the country's fuel and energy balance. It is used as the main type of fuel by tens of thousands of industrial enterprises, it generates over 35 % of electric and thermal energy.

As of December 31, 2022, the average level of gasification of the population of the Russian Federation reached 73,1 %, including: in cities — 73,7 %, in rural areas — 64,8 % with an annual increase in gasified apartments in the amount of 2÷4 times. With unfavorable initial data for gasification, such as a significant distance of the gasified point from the main gas pipeline, or laying in hard-to-reach areas, autonomous gas supply systems based on alternative energy carriers are used: LNG, compressed natural gas (CNG) and liquefied hydrocarbon (petroleum) gases (LPG). At the same time, one of the main tasks in the development of the domestic gas market is the reliability of gas supply to Russian consumers [1].

Comparative analysis shows that liquefied petroleum gases and liquefied natural gas are, at the first approximation, interchangeable energy resources. Diversification of gas supply sources is an effective mechanism for developing the Russian gas industry. It should also be noted that the initial cost of gasification using liquefied natural gas will be much larger than in the case of gasification with liquefied petroleum gas [2–10]. The use of LPG instead of LNG is usually carried out in conditions where it is not possible to gasify the area with natural gas or LNG and is cost-effective in cases where the consumption of liquefied gas does not exceed 100 million m^3/year.

Interchangeable LPG and LNG, similar in structure, parameters and physical and chemical properties, have a key difference in storage temperature. At the same time, due to the versatility of LNG, the latter can be used to regulate both short-term and seasonal fluctuations in gas consumption. The existing experience of gas supply based on LNG suggests that it can be used to regulate the peak unevenness of gas consumption at large production facilities, as well as a motor fuel for various modes of transport. Complex approach to the use of LNG in various sectors of the economy increases the technical and economic indicators of its production, distribution and consumption [10–13].

According to the analysis of the Energy Center of the Moscow School of Management SKOLKOVO the total cost of LNG production in our country is one of the lowest in the world [4; 13] due to the low cost of raw materials — natural gas.

In 2022, the segment of small-scale LNG production in the country consisted of 17 complexes that meet the needs of domestic consumers and boiler houses. By 2025, according to the development roadmap, it is planned to increase the installed capacity of low-tonnage autonomous LNG gasification to 83.3 t/h, thereby adjusting the projected level of gasification in the country upward.

The global demand for LNG supplies in the world tends to grow [4] and, according to forecasts, will reach 700 million tons by 2040. The global LNG market will experience significant growth due to the rapid growth of pipeline infrastructure, combined with favorable government regulation, as well as growing demand for natural gas in the processing and marketing industries, as well as fluctuations in oil prices. An increase in demand for LNG is expected due to the Asian markets, the environmental policy of LNG volatility, as well as its availability.

As you know, the LNG value chain includes liquefaction process, transportation and regasification. LNG complexes include technically and technologically complex: natural gas liquefaction facilities, gas storage facilities and gas delivery modules, a fleet of methane carriers, consumer storage tanks and gasifiers [5; 6].

The availability of LNG systems is primarily due to the absence of the need to install and maintain a network of main pipelines, while it should be noted that due to the improvement of production technology, the quality of LNG is much higher compared to network natural gas [6; 12; 13].

An important factor is the plans for the construction and commissioning of new low-scale units in the central and Far Eastern parts of our country. This fact indicates an increase in the attractiveness of investment projects for the gasification of regions with the help of liquefied natural gas, as well as the use of LNG as a gas motor fuel.

The aforementioned facts indicate the need to increase Russia's share in the LNG industry in order to form and develop successful international cooperation, as well as to achieve a multiplier effect. In case of insufficient interest and participation in the development of the industry, a technical lag is predicted caused by limited access to some key technologies in the field of oil and gas production, a decrease in the efficiency of the economy due to the priority of geopolitical considerations [6].

Taking into account the territorial, climatic and geographic features of Russian regions, the population density of gas-supplying territories, it is necessary to set the task of improving energy supply programs for the regions through the use of small- and medium-tonnage LNG production [6; 13].

The analysis shows that up to 80 % of the production cost of a particular product, including in the development of gas supply projects for consumers remote from mains gas mains, falls on logistics, excluding the cost of equipment and other key factors.

As the analysis shows, the main type of costs in the delivery of liquefied natural gas to the consumer are operations for filling/emptying cryogenic tanks, as well as fuel consumption during the transportation of gas to various categories of consumers. These costs directly depend on the location of the LNG plant relative to the supplied consumers (for example, settlements).

In this regard, the purpose of the study is to illustrate the construction of a logistic model for the functioning of the LNG complex using the example of calculated transport routes of the Kirov region.

As of January 1, 2022, the level of gasification of the Kirov Region with natural gas amounted to 52.3 %. At the moment, the largest cities and a number of villages in the Kirov region have been gasified. according to open sources, 318 of more than 4.2 thousand settlements of the region were supplied with gas as of the indicated date.

Methods

The closest in the proposed model is the model from the article [2]. This article shows a way to optimize logistics routes using the economy matrix method and the center of mass method. The savings matrix method is a method used to minimize distance, time, or cost. When using the matrix method of economy, savings are achieved by combining distribution points on the same route. The resulting value will determine the optimal propagation route. Based on the method of the economy matrix, the problem of vehicle routing is solved, which is an optimization problem of determining the route of distribution with a limitation on the capacity of vehicles. In the given problem customer

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requirements are served by one or more sources. The goal of the routing task method is to find a delivery route that satisfies the requirements or constraints and provides the minimum total cost of distribution.

Low-scale LNG is transported by the following modes of transport road, rail and river [5; 11]. At the same time, it should be noted that in those regions where there is no main gas transport or centralized energy supply, the railway network is also underdeveloped. The same drawback is typical for river transportation.

In view of the aforementioned facts, planning the gasification of territories using LNG acquire to conduct a feasibility study, comparing it with the possibility of gasification with the help of network natural gas. The idea of the study is that a regional gasification project using LNG will be considered more effective if the increase in the price of a unit of LNG (in terms of natural gas) after road transportation from the point of production to the points of consumption is less, than when using gas transportation via a gas pipeline for the same distance. When solving the problem, the capital and operating costs of gas delivery using a gas pipeline and using cryogenic LNG tanks were taken into account. In turn, the center of mass method involves the search for the optimal location of the distribution center position. The location is determined based on the information of the coordinates of the distribution locations, the quantity of products delivered, as well as the cost of delivery of a unit of products.

The disadvantage of this method is the limitation of the matrix economy method. This model involves combining several distribution points into a single route, the sum of the delivery volumes of which does not exceed the volume that can be delivered per flight. Also, this method involves the use of logistics companies as an intermediate link between the manufacturer and the consumer, which is not always profitable.

The calculation of the predicted cost of liquefied natural gas delivered to various categories of consumers by cryogenic tank cars, as well as the cost of natural gas transported through main gas pipelines, showed that LNG transport in one or two directions is more expensive than pipeline gas, which does not contradict world practice and is one of the most compelling reasons for the predominance of trunk gas transport. However, in the case of LNG transportation in three or more supply directions, for example, when implementing a regional gas supply strategy based on liquefied gas, it may well compete with main gas [6; 11; 12].

To determine the distance between settlements of the Kirov region, the coordinates were taken from GOOGLE maps and translated into the local coordinate system MSK-43.

To minimize costs, we will use the method for determining the center of mass:

$$X_c = \frac{\sum_{i=1}^{n}(X_i \cdot Q_i)}{\sum_{i=1}^{n} Q_i}; \quad Y_c = \frac{\sum_{i=1}^{n}(Y_i \cdot Q_i)}{\sum_{i=1}^{n} Q_i}, \qquad (1)$$

where y_i and x_i are the coordinates of the i-th consumer; Q_i — gas consumption by the i-th consumer; X_c and Y_c — coordinates of the center of gravity of freight traffic.

Based on formulas, the optimal coordinates of the LNG plant for gas supply to 264 settlements were obtained.

According to the calculation results, it was obtained that in order to minimize transportation costs, the LNG production plant should be located in the area of the Bogorodskaya village of the municipal formation «Kirov city» of the Kirov region.

When calculating, it was assumed that LNG will be delivered to settlements with a population of more than 200 people, while the percentage of people who will use gas for various needs will be 80 %. The model assumes that the volume of LNG in the storage tanks of the consumer is sufficient to avoid LNG shortages throughout the winter season.

Determination of logistics costs for the delivery of LNG to consumers using road cryogenic tanks

To determine the mileage of road cryogenic tanks, we assume that the cost of transporting LNG will be proportional to the linear distance between cities, then the distance between the plant and consumers will be equal to:

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\,, \tag{2}$$

where x is the coordinate of the x consumer; y is the coordinate of the y consumer.

The result of the calculation according to formula (2) will be a matrix of radial routes for vehicles, where the tank is filled at the LNG plant, travels to the destination, empties, and then returns back to the plant.

To determine the required number of flights to cover the gas demand per year, we use the following formula:

$$n_{ann} = \frac{N_p \cdot V_{ann}^c}{1200 \cdot a_{gc} \cdot V_{ct}}\,, \tag{3}$$

where N_p is the number of gas-supplied population; V_{ann}^c — annual gas consumption by one consumer; a_{gc} is the percentage of gasification (gas coverage); V_{ct} is the gas capacity of one tank.

To determine the total mileage of tankers, we use data on the distance from the proposed location of the LNG plant:

$$\ell_{ct,i} = 2 \cdot L \cdot n_{ann}\,. \tag{4}$$

The total number of working hours for the delivery of LNG to the consumer using road cryogenic tanks is determined by formula 5.

$$\tau_{f,i} = \frac{\tau_t + \dfrac{\ell_{ct,i}}{\vartheta_{ct}}}{\varphi_{sh}}\,, \tag{5}$$

where ϑ_{ct} is the average speed of the tanker, km/h; τ_t is the average time, spent on technological operations, h; φ_{sh} is the shift utilization rate.

We know the distance from the LNG plant and the average speed of the tank, so we can determine the operating time of the tank to deliver the required volume of LNG per month to the consumer:

$$T = \sum \tau_{f,i}\,. \tag{6}$$

The number of road cryogenic tanks is determined by the formula:

$$N_{ct} = \left[\frac{T}{n_{wd} \cdot t_{sh}} \right], \tag{7}$$

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where t_{sh} is the duration of the shift, h; n_{wd} is the number of working days.

When moving the tank, fuel is spent on setting the vehicle in motion, as well as on the operation of the cooling system of the tank. In accordance with this fact, we have:

$$C_{df} = \frac{\sum(d_{0i} + d_{0j}) \cdot q_{ref}}{\vartheta_{ct}} + \frac{C'_{df} \cdot q_{df} \cdot \ell_{ct} \cdot (1 + K_f)}{100}, \quad (8)$$

where C'_{df} is the cost of 1 liter of diesel fuel, rub/l; q_{ref} is the fuel consumption for the operation of the refrigerator l/h; q_{df} is the fuel consumption of the tank l/100 km; K_f is the coefficient of increase in fuel consumption during the transportation of dangerous cargo, taken in accordance with (Decree of the Ministry of Transport of the Russian Federation dated March 14, 2008. No. AM-23-p «Implementation of the guidelines «Norms for the consumption of fuels and lubricants in road transport»).

Since the gasification area remains unchanged and the number of consumers does not change, the model does not take into account the construction of a natural gas liquefaction plant.

In addition to the cost of cars, we calculate the cost of wages for drivers per month:

$$C_w = C_d \cdot N_{ct}, \quad (9)$$

where C_d is the driver's salary, rub/month.

And finally, we calculate the future possible gross profit:

$$GP_{LNG} = V_{ann} \cdot P_{LNG} - C_w - C_{df} - C_{LNG}, \quad (10)$$

where P_{LNG} is the cost of LNG, rub/m^3.

The initial data accepted for calculation are presented in table 1.

Table 1

Initial data

Name of input data	Quantity	Dimension
Annual gas requirement per person	400.0	m^3
Useful volume of a cryogenic tank	53.5	m^3
Required time for technological operations	0.5	hour
Average speed of a cryogenic tank	50.0	km/h
Cryogenic tank working shift	8.0	hour
Fuel consumption increase factor	15.0	%
Tanker fuel consumption	44.0	l/100 km
Shift utilization rate	0.85	–
Cryogenic tank driver salary	100 000	rub/month
The cost of LNG	14 500.0	rub/1 000 m^3 LNG
Diesel price	54.0	rub/l
Cryogenic tank truck cost	26 077 000	rub

Results and discussion

Since this task considers settlements with a relatively small population, the volume of most cryogenic road tanks will be sufficient to meet the needs of the population of several settlements.

Formulas (2)–(10) describe scheme A of figure 1.

To optimize the route of the cryogenic tank, it is proposed to subjoin additional settlements along the route for maximum use of the valuable volume of the tank.

The distance traveled along the pendulum route indicated in diagram A will be equal to:

$$L_{ij} = 2 \cdot d_{0i} + 2 \cdot d_{0j} . \quad (11)$$

In order to take into account a larger volume of consumption to settlements than a cryogenic tank can cover per flight, we give the formula to the following form:

$$L_{ij} = \sum \left\lceil \frac{q_{ij}}{V_{ct}} \right\rceil \cdot 2 \cdot d_{ij} , \quad (12)$$

where q_{ij} is the city's gas need; $\left\lceil \frac{q_{ij}}{V_{ct}} \right\rceil$ is the number of flights of the cryogenic tank.

The distance traveled along route B (fig. 2) is described by the formula:

$$L_{ij} = \left\lceil \frac{\sum q_{ij}}{V_{ct}} \right\rceil \cdot \sum d_{ij} . \quad (13)$$

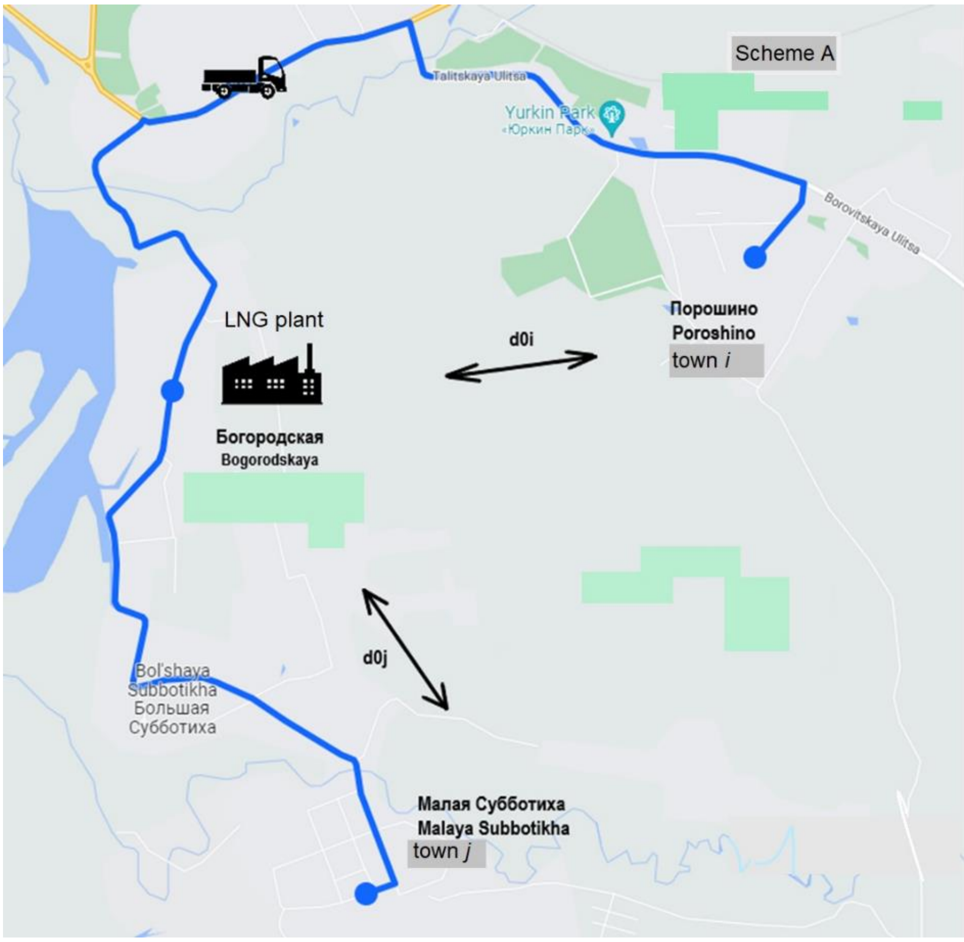

Figure 1. *Gas delivery option according to the dead-end scheme A (authors drawing)*

To determine the distance gain, we subtract from (12) the value (13):

$$L_{ij} = \sum \left(\left\lceil \frac{q_{ij}}{V_{ct}} \right\rceil \cdot 2 \cdot d_{ij} \right) - \left\lceil \frac{\sum q_{ij}}{V_{ct}} \right\rceil \cdot \sum d_{ij} . \quad (14)$$

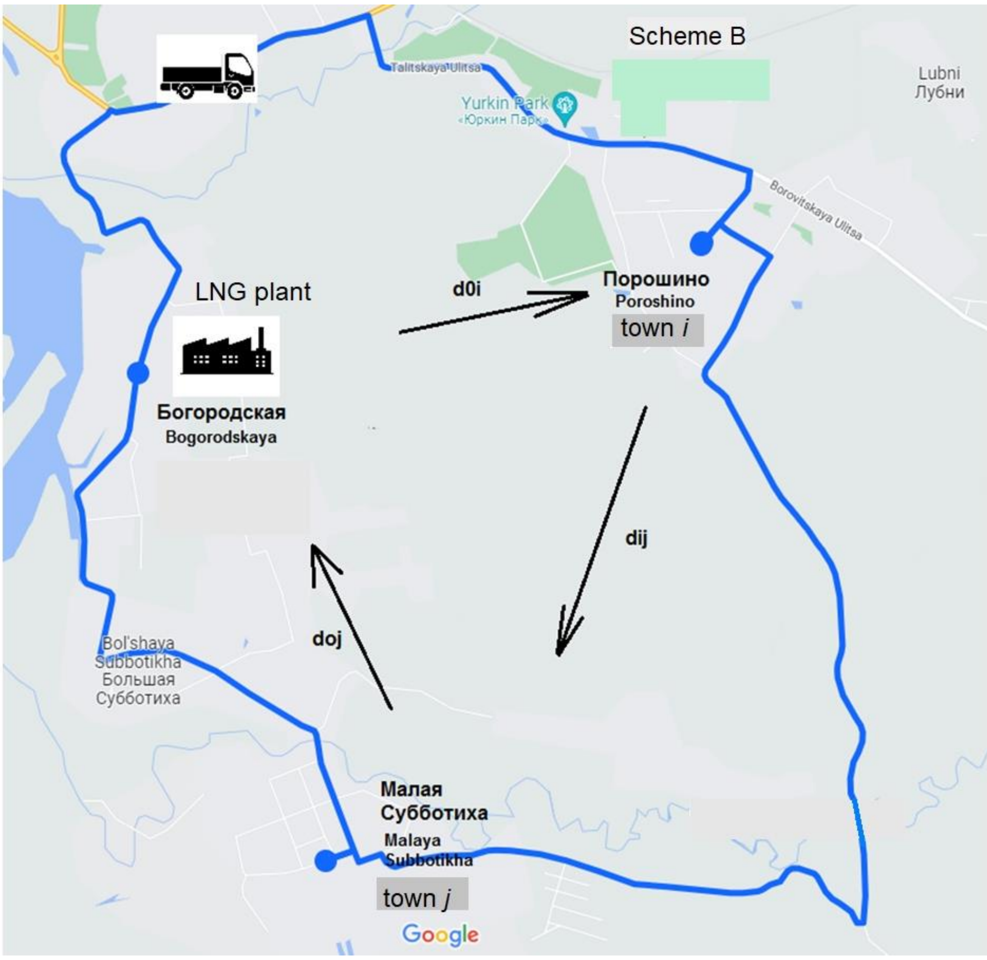

Figure 2. *Gas delivery option according to the ring scheme B (authors drawing)*

The meaning of formula (14) lies in the reduction of mileage by cars when replacing two pendulum routes with a circular one, consisting of two points. According to this formula, the calculation is performed for each possible bundle of cities.

The result of calculations using the formula (14) will be a matrix of kilometer gains, where the right side of the matrix will be filled with distances between points (d_{ij}), and the left side with kilometer gains (L_{ij}).

Next, we search for optimal ring routes in accordance with the following algorithm.

Stage 1.

Each route originates in the city of the installation of the plant for the production of liquefied natural gas.

Among the obtained values, we find the route with the highest «gain» value:

$$L\max = \max_{i,j} L(i, j) = S(i^*, j^*). \quad (15)$$

In this case, the following conditions must be met:

1. Gas-supplied settlements i^* and j^* are not part of the same transport route for gas delivery.
2. Gas-supplied settlements i^* and j^* are not the starting or ending point of those routes, in which they are included.

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3. A bunch of gas-supplied settlements (i^* j^*) was not considered at the previous steps of the algorithm.

Stage 2.

The route that includes gas-supplied settlement i* is denoted as transport route 1. Accordingly, the route that includes gas-supplied settlement j^* is denoted as transport route 2.

Routes 1 and 2 are combined into one common circular route X. We will assume that gas-supplied settlement i^* is the end point of transport route 1 and gas-supplied settlement j^* is the starting point of transport route 2. When combining transport routes 1 and 2, we observe the following conditions:

1. The sequence of locations of points on transport route 1 from the beginning to gas-supplied settlement i^* does not change.
2. Item i^* is linked to item j^*.
3. The sequence of location of points on transport route 2 from gas-supplied settlement j^* to the end does not change.

We repeat stages 1–2 until the next repetition fails to find an $L_{\max}$ that fulfills the three conditions from step 1.

Stage 3.

The total mileage of vehicles is calculated for the received ring routes, as well as for the pendulum routes.

According to formula (5)–(7), (9)–(10), the possible profit is determined.

Fuel costs for looped routes are determined by the formula:

$$C_{df} = \frac{(\sum(d_{ij}) - d_{j0})}{\vartheta_{ct}} \cdot \frac{q_{ref}}{100} + \frac{C'_{df} \cdot q_{df} \cdot \ell_{ct} \cdot (1 + K_f)}{100}. \qquad (16)$$

As a result of optimization, the following cities were included in the ring routes: Kamsky; Gordino; Varankiny; Lytka; Shapta; Kugusherga; Lundanka and others.

Thus, 83 ring routes were obtained, which included 162 settlements out of 264.

The calculation results are shown in table 2.

Table 2

Results of optimization calculations

Indicator	Quantity before optimization	Quantity after optimization	Dimension
Total mileage of tankers	138 899.5	109710.5	km
Fuel costs	3 795 373	2 997 795	rub
Labor costs for drivers	2 000 000	1 200 000	rub
Costs for the purchase of cryogenic tanks	521 540 000	312 924 000	rub
LNG production costs	530 040 145	530 040 145	rub
LNG sales revenue	1 371 442 258	1 371 442 258	rub
Gross profit for the year of operation of the logistics network	314 066 739.9	524 280 317.9	rub

Conclusion

1. The proposed transport and logistics model makes it possible to reduce the amount of capital investments in the logistics network of the energy supply of the territories under consideration by reducing the number of vehicles for transporting LNG, reducing the number of personnel servicing tankers, and reducing the amount of fuel required for cryogenic tanks.

2. The advantage of this proposed transport and logistics model is the ability to take into account the terrain features of the area selected for gas supply, the speed of transport tanks for a more accurate determination of the level of current costs.
3. This model allows the most complete use of the potential of road cryogenic tanks for the delivery of LNG.
4. The comparison of the logistics scheme for the delivery of LNG and the traditional transportation of natural gas through pipelines led to the conclusion that the savings in the reduced costs when using LNG will increase as the consumer moves away from the gas supply source. For example, if the end consumer is 150–200 km away from the gas supply base, the savings will exceed 100 million rubles/year.
5. The proposed optimization of the logistics scheme for the delivery of LNG to consumers for the conditions of the Kirov region is able to increase the gross profit from the project by 40 % by reducing the number of required vehicle fleet, labor costs, as well as reducing the total mileage of tankers.

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Газоснабжение потребителей на базе сжиженного природного газа

Аннотация. Определение оптимальной альтернативы природному газу представляется в виде использования для энергообеспечения бытовых, коммунально-бытовых и производственных потребителей сжиженных газов. Результаты предварительного технико-экономического сравнения альтернативных энергоносителей — сжиженных углеводородных и сжиженного природного газов — однозначно подтверждают эффективность и конкурентоспособность последнего. В данной работе исследуются способы оптимальной доставки природного газа потребителям, рассмотрены варианты трубопроводного и автомобильного транспорта. Предложен метод оценки экономичной доставки газа потребителям, основанный на решении логистико-математической задачи, и позволяющий определить оптимальный радиус доставки сжиженного природного газа различным категориям потребителей в зависимости от годового газопотребления, удаленности потребителей от опорных пунктов газоснабжения — источников газа, в качестве которых выступают: газораспределительная станция — в варианте трубопроводного транспорта и комплекс ожижения природного газа — в варианте доставки газа автомобильными криогенными цистернами. Для проверки работоспособности представленного алгоритма проведена оценка рационального размещения комплекса по ожижению природного газа по координатам негазифицированных населенных пунктов Кировской области путем решения логистической задачи по методу условного центра масс. Годовая прибыль для конкретных условий проектирования составила 524.28 млн рублей. Полученные результаты исследования по применению альтернативных источников газоснабжения показывают высокие возможности использования сжиженного природного газа для всех коммунально-бытовых и производственных нужд потребителей, взаимоудаленных от магистрального газопровода сетевого природного газа.

Ключевые слова: сжиженный природный газ; природный газ; газоснабжение; криогенный резервуар; энергоэффективность; транспорт; энергосбережение; численные методы; экономическая эффективность; оптимизация

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