Logistic and mathematical model of application efficiency liquefied natural gas

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Abstract. Today, natural gas, with certain advantages over other fossil fuels, is one of the main energy resources for various industries and housing and communal services. As a rule, when choosing a gas transportation method for different categories of consumers, several options are considered depending on the mutual removal of the source and the consumer – construction of a gas pipeline or the creation of a liquefied gas infrastructure. Analysis of energy supply problems in some constituent entities of the Russian Federation showed that a reasonable choice of technological parameters of a gas distribution system based on liquefied natural gas (LNG) is an urgent task that requires preliminary modeling. The paper proposes a solution to a particular problem of supplying consumers with liquefied natural gas, a logistic model for the optimal functioning of the system for the complex: LNG plant – consumer. Based on the results of calculations for the conditions of the Republic of Karelia, recommendations are proposed for the optimal location of the source (LNG plant) and optimization of the transport component.

1. Introduction

The Russian Federation, as the largest energy country, has 19.1% (38 trillion m$^3$) of the world's confirmed natural gas reserves and ranks second in terms of production – 679 billion m$^3$ (based on the results of 2019). In Russia as a whole, according to Federal Agency for Mineral Resources (Rosnedra), at the end of 2019, the increase in gas reserves due to geological exploration is tentatively estimated at 1.354 trillion m$^3$. In 2019, the total gas production (natural and associated petroleum) in the Russian Federation reached a record level over the past 19 years – 737.8 billion m$^3$. For many years, Russian pipeline gas has held a leading position in European countries (in 2019, Russian gas imports exceeded 200 billion m$^3$, or 45% of demand), entered the markets of the Asia – Pacific region, in addition, the production and delivery of liquefied natural gas, the production level of which is planned to reach 80 – 120 million tons per year by 2035.

Natural gas is a leading component of the country's fuel and energy balance. It forms the basis of energy consumption of tens of thousands of industrial enterprises, it generates over 35% of electric and thermal energy. The total supply of gas to consumers under the Unified Gas Supply System is more than 75 billion m$^3$, in addition, 17 million tons of liquefied hydrocarbon gases (LHG) and 29.5 million tons of LNG are produced and supplied.

The main consumers of gas in the industry are enterprises of the electric power industry, metallurgy, chemical industry, which account for more than half of the gas consumed in Russia.

The most important consumer of natural gas is also the housing and utilities sector of the country, which accounts for 20% of consumed gas (11% – population, 8% – utilities sector).
As of January 1, 2020, the average level of gasification of the population of the Russian Federation is 70.1 %, including: in cities – 71.9 %, in rural areas – 59.4 %, with an annual increase in gasified apartments in the amount of 2–4 times. In remote and hard-to-reach areas, where the network gas supply is not feasible for economic and technical reasons, autonomous gas supply systems are used based on alternative energy sources: LNG, compressed natural gas (CNG) and liquefied petroleum gases.

If the level of gasification of the population of the European part of the country is high enough and reaches 75–80 and more percent, then gasification of Siberia and the Far East is at the level of 30–35 %. Since these data are of strategic importance for the country's development, the energy strategy of the Russian Federation for the period up to 2035 sets the following tasks:

- improvement of the domestic gas market and efficient satisfaction of domestic gas demand;
- development of the production of low-tonnage liquefied natural gas and the formation on its basis of the internal market of liquefied natural gas as a tool for ensuring energy security of territories remote from the Unified Gas Supply System;
- formation of oil and gas mineral resource centers in new regions (Eastern Siberia and the Far East) and on the continental shelf of the Russian Federation;
- development of the main gas transportation infrastructure (including the creation of gas transportation infrastructure in Eastern Siberia and the Far East);
- socially and economically feasible increase in the level of gasification of the constituent entities of the Russian Federation, taking into account the specifics of regional fuel and energy balances, including the creation of conditions for the primary supply of gas to land plots involved in circulation for housing construction, as part of the implementation of national projects and national programs (by 2024 74.7 %; by 2035 - 82.9 %)

Despite the wide scale of gasification of the country, the level of gas supply to the rural population does not meet modern requirements and potential capabilities of the Unified Gas Supply System. More than half of the country's rural population is not covered by networked natural gas. Gas supply to apartments is reduced to the use of bottled liquefied petroleum gas. The latter is mainly implemented for the needs of food preparation, while the rest of the household and household needs (heating and hot water supply), as well as industrial needs are covered by solid and liquid fuels. In this regard, the strategic task set by the President of the Russian Federation and enshrined in Federal Law No 69 of March 31, 1999 “Gas Supply in the Russian Federation”, which provides for extensive gasification based on network natural gas, as well as using alternative sources (liquefied natural gas, liquefied hydrocarbon gases, compressed natural gas) in the area of the Unified Gas Supply System (regional gas supply system) and in areas without gas supply systems, is a priority area for the development of the gas industry in general and its gas distribution industry in particular.

At present, the gas distribution systems of cities and settlements are elaborate technologically, organizationally and economically interconnected and centrally controlled complex of facilities intended for the production, transportation, storage and supply of gas, including gas networks of various pressure categories, underground gas storage facilities, gas distribution stations, reduction points, gas-using equipment. This circumstance predetermines the variety of system-forming ties and the complex nature of the interaction of factors that determine the mechanism of functioning of gas distribution systems [1, 2]. Reliability of gas supply to Russian consumers is one of the main tasks in the development of the domestic gas market [3].

Development of branch of manufacture liquefied natural gas for maintenance of internal consumption of the country and as for export abroad becomes actual in connection with a rise in prices on energy carriers and growth power consumption [4, 5].

Supply liquefied natural gas possesses a number of advantages which in some cases are defining at a choice of system of a gas–transport network [6]. To such advantages concern [7, 8]:

- an opportunity of storage under small superfluous pressure at temperature about 112 K;
- nontoxic;
- high caloric content (in comparison with other kinds of fuel);
• low temperature of boiling – a guarantee of full evaporation LNG at the lowest temperatures of air;
• efficiency and convenience of storage, transportation and consumption (at liquefied natural gas its density increases in 600 times);
• LNG can be delivered to the consumer by any kind of transport (including intercontinental transportations), etc.
• Supply of consumers based on LNG is economically justified in following conditions [9, 10]:
  • small volumes of consumption of gas the object removed from the main gas main;
  • a stable seismic conditions on a site of prospective construction of a gas main;
  • a complex lay of land on a prospective line of construction of a gas main;
  • the gasified object or a prospective line of construction of a gas main are in area with a unique natural landscape;
• presence of a formidable barrier on a prospective line of construction of a gas main (the sea, the river, mountains).
  For optimum operation of all LNG–complex to build a strong relationship between its main elements [11, 12]. The liquefaction complex is an important and capital–intensive component in the processing chain of transport of natural gas, as a strong point of gas supply systems. with a large number of settlements that require natural gas supply and their significant dispersal of the definition of optimal location liquefaction plant requires a pre-feasibility studies.

2. Materials and Methods
Transportation of liquefied natural gas is significantly more economical than pipeline transportation. This applies both to the transportation of large volumes of gas over long distances by various types of transport, and to the delivery of small volumes of LNG over short distances [1, 13].

At the same time, the advantage of large–capacity transportation of gas in liquefied form begins with distances to consumers over 2500–3000 km [1, 13]. The bulk of the cost comes from handling operations, and LNG also requires more capital investments in infrastructure initially. The creation of LNG infrastructure for low–tonnage transportation will be beneficial in cases where the construction of a gas pipeline is economically unprofitable (due to the difficult terrain, significant distance between the consumer and the source, the consumer needs gas in small volumes, and other justified reasons).

The choice of gas delivery option in each specific case is carried out by means of a comparative technical and economic analysis [14, 15].

The LNG infrastructure includes technically and technologically elaborate facilities for production, storage, transportation and regasification [16].

In the process of designing an LNG production, an important issue is solving the problem of locating a gas supply source [13, 17, 18] - in our case, a plant for the production of liquefied gas. The aim of the study is to build a logistic model for the functioning of the LNG complex using the example of the Republic of Karelia.

3. Search for the optimal location of the LNG plant in the Republic of Karelia
To date, the level of gasification of the republic with network natural gas does not exceed 8.5%. The specificity of the gasification of this region lies in the fact that the gas distribution networks are far enough from the main pipelines of the network natural gas, and the process of gasification with natural gas began relatively recently, in 1996.

Determination of the optimal location for the liquefied natural gas plant is based on the document “On Approval of the Regional Program “Gasification of the Republic of Karelia for 2017–2021”, as well as “Adjustment of the General Schemes of Gas Supply and Gasification of Regions of the Russian Federation. Republic of Karelia” it was found that at the time of the implementation of the regional gasification program of the Republic of Karelia, 771 settlements will remain ungasified. 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 mod-
el assumes that the volume of LNG in the storage tanks of the consumer is sufficient to avoid LNG shortages throughout the winter season.

To determine the distance between cities, the coordinates were taken from GOOGLE maps and translated into the local coordinate system MSK–10.

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

\[
X_{cm} = \frac{\sum_{i=1}^{n} (X_i \cdot Q_i)}{\sum_{i=1}^{n} Q_i}; \tag{1}
\]

\[
Y_{cm} = \frac{\sum_{i=1}^{n} (Y_i \cdot Q_i)}{\sum_{i=1}^{n} Q_i}. \tag{2}
\]

where:

- \(Y_i\) and \(X_i\) are the coordinates of the \(i\)-th consumer;
- \(Q_i\) is the gas consumption by the \(i\)-th consumer;
- \(X_{cm}\) and \(Y_{cm}\) are the coordinates of the center of gravity of freight traffic.

Based on formulas (1), (2), the optimal coordinates of the LNG plant for gas supply to 137 settlements were determined.

We assume that the cost of LNG transportation will be proportional to the linear distance between cities, then the distance between the plant and consumers will be determined by the formula [13]:

\[
L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, \tag{3}
\]

where \(x\) is the coordinate of the \(x\) consumer; \(y\) is the coordinate of the \(y\) consumer.

The volume of gas consumed per year is calculated by the formula:

\[
V_{ann} = \frac{N_p \cdot V_c^{\text{ann}}}{100 \cdot a_{gc}}, \tag{4}
\]

where:

- \(N_p\) is the number of gas-supplied population;
- \(V_c^{\text{ann}}\) – annual gas consumption by one consumer;
- \(a_{gc}\) is the percentage of gasification (gas coverage).

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

\[
n_{\text{ann}} = \frac{V_{\text{ann}}}{V_{\text{ct}}}, \tag{5}
\]

where \(V_{\text{ct}}\) is the gas capacity of one cryogenic tank.

To determine the mileage of each of the cryogenic tanks, we will use info of the distance from the proposed location of the LNG plant:

\[
\ell_{\text{ct}} = \frac{L}{n_{\text{ann}}}. \tag{6}
\]

Knowing the distance from the LNG plant and the average speed of the tanker truck, we calculate the time spent on one trip (both ways):

\[
\tau = \frac{120 \cdot L}{\vartheta_{\text{ct}}}, \tag{7}
\]

where \(\vartheta_{\text{ct}}\) – average speed of the cryogenic tank.
The number of flights per month is calculated by the formula:

\[ m = \frac{t \cdot \varphi}{22 \cdot \tau} , \]  

(8)

where:
- \( t \) is the time of movement of the tanker;
- \( \varphi \) is the utilization rate of the shift.

Calculate the number of tank trucks to transport the required volume of gas:

\[ n_{ct} = \frac{n_{am}}{12 \cdot m} , \]  

(9)

where 12 is the number of months for LNG delivery.

In addition, we will take into account the costs of refueling cryogenic tanks with diesel fuel:

\[ C_{df} = P_{df} \cdot \ell_{ct} , \]  

(10)

where \( P_{df} \) is the fuel price of one liter.

As a result, the cost of production will consist of the following values:

\[ C_{LNG} = V_{ct} \cdot n_{am} \cdot \]  

(11)

Based on the results of the numerical analysis, we take the production cost of one ton of LNG equal to 25000 rubles.

In addition to the costs of tankers, we will calculate the costs of wages for drivers:

\[ C_d = 12 \cdot S_d \cdot n_{ct} . \]  

(12)

where \( S_d \) is the salary of one driver.

Finally, we will calculate the future potential profit:

\[ PP_{LNG} = V_{am} \cdot P_{LNG} - C_d - C_{df} - C_{LNG} \]  

(13)

where \( P_{LNG} \) is the cost of one m³ of gas.

4. Results and Discussion

The calculation results are presented in tables 1, 2 and 3. Figure 1 shows a graphical interpretation of the calculation results.

![Figure 1. A graphical interpretation of the calculation results.](image-url)
Table 1. Initial data for calculation.

| Locality         | Latitude      | Longitude      | Latitude | Longitude | Center of mass | Number of gas-supplied population |
|------------------|---------------|----------------|----------|-----------|----------------|-----------------------------------|
| Besovec          | 61°51'40.94" N | 34°9'40.97" E  | 55.75    | 37.61     | 12.28          | 120                               |
| Vilga            | 61°49'5.00" N  | 34°43'9.00" E  | 61.82    | 34.08     | 14.53          | 1053                              |
| Derevyanka       | 61°33'43.79" N | 34°279.23" E   | 61.55    | 34.34     | 26.64          | 1622                              |
| Derevyannoe      | 61°37'4.44" N  | 34°37'51.19" E | 61.62    | 34.62     | 24.83          | 1177                              |
| Zaozer'e         | 61°51'49.49" N | 34°22'51.22" E | 61.85    | 34.37     | 7.72           | 1337                              |
| Ladva            | 61°21'21.45" N | 34°38'1.89" E  | 61.35    | 34.63     | 49.38          | 2145                              |
| Ladva–Vetka      | 61°21'32.89" N | 34°27'19.96" E | 61.35    | 34.45     | 49.03          | 983                               |
| Meliorativnyj    | 61°51'53.96" N | 34°14'27.22" E | 61.85    | 34.23     | 9.56           | 2475                              |
| Novaya Vilga     | 61°48'38.03" N | 34°9'3.99" E   | 61.80    | 34.15     | 10.57          | 1579                              |
| Paj              | 61°12'26.61" N | 34°26'16.48" E | 61.20    | 34.43     | 65.78          | 498                               |
| Rybreka          | 61°17'15.19" N | 35°31'4.74" E  | 61.28    | 35.52     | 84.13          | 467                               |
| Uzhessel'ga      | 61°43'12.81" N | 34°29'26.26" E | 61.72    | 34.48     | 11.29          | 254                               |
| Chalna–I         | 61°54'26.31" C | 34°9'32.93" E  | 61.90    | 34.15     | 15.93          | 1866                              |
| Shyoltzero       | 61°22'10.20" N | 35°21'24.62" E | 61.36    | 35.35     | 71.62          | 878                               |
| Shoksha          | 61°273.11"C N  | 35° 254.07" E  | 61.45    | 35.03     | 53.45          | 167                               |
| Shujskaya        | 61°56'37.65" N | 34°14'46.25" E | 61.93    | 34.23     | 17.33          | 781                               |
| Shuya            | 61°53'55.21" N | 34°14'3.02" E  | 61.88    | 34.23     | 12.94          | 3139                              |
| Petrozavodsk     | 61°47'46" N    | 34°20'57" E    | 61.79    | 34.35     |                | 281023                            |

Table 2. Calculation results.

| Locality         | Volume of gas consumed per year [mln m³] | Required number of flights | Distance from the LNG plant [km] | Time spent on one trip | Number of flights |
|------------------|------------------------------------------|-----------------------------|----------------------------------|-----------------------|------------------|
| Besovec          | 124.01                                   | 12918                       | 158.65                           | 25                    | 25               |
| Vilga            | 1088.17                                  | 113351                      | 1647.33                          | 30                    | 21               |
| Derevyanka       | 1676.18                                  | 174602                      | 4651.75                          | 54                    | 12               |
| Derevyannoe      | 1216.32                                  | 126699                      | 3146.22                          | 50                    | 12               |
| Zaozer'e         | 1381.66                                  | 143923                      | 1111.28                          | 16                    | 40               |
| Ladva            | 2216.65                                  | 230901                      | 11401.58                         | 99                    | 6                |
| Ladva–Vetka      | 1015.83                                  | 105816                      | 5187.83                          | 99                    | 6                |
| Meliorativnyj    | 2557.67                                  | 266424                      | 2548.18                          | 20                    | 32               |
| Novaya Vilga     | 1631.742                                 | 169973                      | 1796.43                          | 22                    | 29               |
| Paj              | 514.64                                   | 53608                       | 3526.36                          | 132                   | 4                |
| Rybreka          | 482.60                                   | 50271                       | 4229.20                          | 169                   | 3                |
| Uzhessel'ga      | 262.48                                   | 27342                       | 308.56                           | 23                    | 28               |
| Chalna–I         | 1928.33                                  | 200868                      | 3199.42                          | 32                    | 20               |
| Shyoltzero       | 907.33                                   | 94513                       | 6768.76                          | 144                   | 4                |
| Shoksha          | 172.58                                   | 17977                       | 960.77                           | 107                   | 6                |
| Shujskaya        | 807.09                                   | 84072                       | 1456.84                          | 35                    | 18               |
| Shuya            | 3243.85                                  | 337901                      | 4370.91                          | 26                    | 24               |
| Petrozavodsk     |                                          |                            | 56470.08                         |                       |                  |
Table 3. Calculation results of the future potential profit.

| Locality       | Number of tanks per working day | Costs of refueling cryogenic tanks with diesel fuel [mln rub] | Costs of wages for drivers [mln rub] | Future potential profit [mln rub] |
|----------------|---------------------------------|-------------------------------------------------------------|--------------------------------------|----------------------------------|
| Besovec        | 3                               | 7.46                                                        | 2.16                                 | 679.87                           |
| Vilga          | 22                              | 77.43                                                       | 15.84                                | 5956.97                          |
| Derevyanka     | 59                              | 218.63                                                      | 42.48                                | 9058.44                          |
| Derevyannoe    | 43                              | 147.87                                                      | 30.96                                | 6583.88                          |
| Zaozer'e       | 15                              | 52.23                                                       | 10.80                                | 7618.99                          |
| Ladva          | 156                             | 535.88                                                      | 112.32                               | 11676.37                         |
| Ladva–Vetka    | 72                              | 243.83                                                      | 51.84                                | 5352.37                          |
| Meliorativnyj  | 34                              | 119.77                                                      | 24.48                                | 14076.40                         |
| Novaya Vilga   | 24                              | 84.43                                                       | 17.28                                | 8970.77                          |
| Paj            | 55                              | 165.74                                                      | 39.60                                | 2656.03                          |
| Rybreka        | 68                              | 198.77                                                      | 48.96                                | 2435.52                          |
| Uzhesel'ga     | 4                               | 14.51                                                       | 2.88                                 | 1442.03                          |
| Chalna–I       | 41                              | 150.37                                                      | 29.52                                | 10541.61                         |
| Shyoitozero    | 96                              | 318.13                                                      | 69.12                                | 4657.49                          |
| Shoksha        | 13                              | 45.16                                                       | 9.36                                 | 905.02                           |
| Shujskaya      | 19                              | 68.47                                                       | 13.68                                | 4405.25                          |
| Shuya          | 58                              | 205.43                                                      | 41.76                                | 17788.61                         |
| Petrozavodsk   |                                 | 2654.10                                                      | 563.04                               | 114805.60                        |

According to the results of the calculation, the possible profit for the year will be 112.298 million rubles including the purchase of 15065 units of tanks for the transportation of LNG.

5. Conclusion
The lack of theoretical elaboration of the issue under consideration, the need for practical recommendations to improve an integrated approach to the creation of LNG infrastructure determined the goal and objectives of this work.

As the results show, the use of natural gas in liquefied form contributes to the diversification of energy supply, allowing to improve the structure of energy supply sources, increasing the reliability and energy security of the country, and medium– and low–tonnage LNG production can play a significant role in the development of regions of the Russian Federation, solving the problem of the availability of an efficient energy resource.

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