Comparison of the Multi-Directional Delivery Efficiency of Low-Tonnage LNG and Pipeline Gas in Russia

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Abstract. One of the fastest growing areas of the gas industry is low-tonnage LNG production, which allows to improve the efficiency of the gas distribution process due to the flexibility of the supply routes. A small number of articles devoted to this field, indicate that LNG is less attractive than pipeline gas from an economic point of view, however, such estimates do not take into account the flexibility of LNG delivery routes. This article proposes a model for a comparative assessment of the LNG and pipeline gas price. The distinctive feature of the model is the possibility of changing the number of delivery directions, which makes it possible to evaluate the impact of the LNG transportation flexibility. The results show that in contrast to the pipeline gas, the increasing in the number of supply routes with the same total volume of deliveries, does not reflect on the price of LNG. In addition, this causes a decrease in the minimum delivery distance at which LNG automobile transportation can compete with a pipeline.

1. Introduction
At present, natural gas is one of the most demanded types of energy resources, despite the intensive development of renewable energy. According to significant number of forecasts, its position in the 21st century will only increase because of the cost, energy and environmental characteristics [1]. In this regard, the issues of increasing the efficiency of gas use and reducing its price for consumers are becoming more urgent. These issues are also significant for Russia, which ranks second in terms of proven reserves of natural gas, as well as second in terms of its production. In 2016, only PJSC Gazprom supplied more than 356.6 billion cubic meters of natural gas to 20 countries [2]. Transportation of natural gas is carried out, as a rule, through a system of gas pipelines [3], which is associated with a number of territorial, political and economic problems. Firstly, it is necessary to take into account the peculiarities of the terrain, along which the pipeline is laid. Secondly, carrying out a gas pipeline through the territory of other countries requires a consent of local authorities. Thirdly, delivery through the pipeline is absolutely inflexible and does not allow to change the direction of gas supplies in a short time. Fourthly, the gas pipeline system requires constant technical support throughout its entire length. Nevertheless, this is the most frequently used method of gas delivery to a significant part of the global market [4]. An alternative to pipeline transport is the use of liquefied natural gas (LNG) technological chains, which became a point of interest in recent decades with the desire to solve the problems of gas pipelines operation. Large and medium volumes of LNG over a long distance as a rule shipped by a Maritime transport [5]. In the case of low-tonnage LNG production, the delivery can be carried out by automobile, rail and river transport. Given that transport networks are developed much better than pipelines, this allows diversifying the supply routes.
In major part of research papers, the comparison of LNG and pipeline gas prices is carried out on the basis of gasification projects consideration for one specific point of gas supply. However, this approach does not allow estimating the effect of the technological schemes flexibility. In this regard, the aim of this paper is to assess the feasibility of low-tonnage LNG multi-directional delivery based on a comparison of its unit price with the price of pipeline gas.

2. Methodology
The assessment was conducted for Russian economy conditions, where are significant problems with gas supply in the far regions. According to some estimates, between 40% and 50% of the country’s territory does not have access to centralized energy supply, with the major part of these locations in the Eastern part of Russia [6]. Despite this, the annual gas consumption in the domestic market is more than 450 billion cubic meters, and the forecasted growth is 1-3% per year.
In general, there are more than 18,000 small settlements on the territory of Russia, about 30-40% of which are not gasified [7]. The construction of gas pipelines in these settlements cannot be met without significant state support, due to the capital intensity of such projects, and, consequently, significant unit costs at low volumes of gas consumption.

2.1. Formatting the title
The strategy of Russian territory gasification is based on the development of the main gas pipeline, the continuation of which for Siberia territory is planned only in a long term. Partially the problem of far regions gasification could be solved by the development of the LNG industry [8]. In addition to the objective need of liquefaction, the LNG production process is associated with substantial expenses for regasification [9, 10]. However, when we talk about small volumes of consumption, it is possible to use modern mobile power plants that can function on LNG due to the regasification systems included in their structure [11]. It allows to reduce production costs significantly, as well as increase the attractiveness of the trigeneration technological schemes [12]. The cost of such facilities operating on LNG is slightly higher (10-15%) than the equipment operating on a pipeline gas. Therefore, conducted assessment did not take into account the difference in the costs associated with energy generating facilities.
Transportation of low-tonnage LNG is possible by automobile, rail and river transport. However, the railway network is not sufficiently developed in regions that do not have access to centralized energy supply [13]. The same drawback is typical for river shipping, and in this connection, attention in this article was focused on automobile delivery.
The idea behind this article is that the regional gasification project with using LNG will be considered more efficient if the increase in the unit price of LNG (in terms of natural gas) after automobile transportation from the point of production to the points of consumption will be lower than with using a pipeline for the same distance. At the same time, distance delivery means that there is at least one point of consumption within the radius of this distance; however, it must be taken into account that the number of such points may vary significantly (Figure 1).

![Figure 1. Scope of the article](image_url)

For the purpose of the assessment and to show the dynamics of pipeline gas price changing, the maximum number of delivery directions accepted equal to 5. The assessment was carried out for LNG
plant with a capacity of 22,500 tons of LNG per year, which is equal to 31,056 million cubic meters of natural gas. In original, all calculations were made in Russian Rubles. The conversion was carried out at the rate of 58 RUR per 1 USD.

2.2. Liquefaction plant CAPEX and OPEX

The structure of the plant construction CAPEX is shown in Figure 2-B. The depreciation rate is 10%. OPEX of the LNG plant consist of the purchased natural gas price, the salary of employees, the cost of electricity and unforeseen expenses. The structure of the OPEX for the production of one ton of LNG is shown in Figure 2-A.

![Figure 2. LNG plant OPEX (A) and CAPEX (B)](image)

2.3. Automobile delivery CAPEX and OPEX

CAPEX of automobile delivery are limited by the purchase of trailers with tanks. Based on the analysis of acceptable vehicles, trailers at a price of 224 137.93 USD, which are capable to deliver 19 tons of LNG per voyage were chosen. Automobile delivery OPEX consist of the fuel price (0.655 USD per liter), drivers’ wages, maintenance costs and unforeseen expenses. The wage of drivers is equal to the average market rate for Russia - 4.268 USD per hour, including all taxes and fees. At the same time, depending on the transportation distance, increasing coefficient was introduced, according to table 1.

![Table 1. Increasing coefficient for drivers’ wages](image)

In addition to the basic 5%, the amount of unforeseen expenses takes into account the risks arising with the increase in the transportation distance, such as breakage, traffic accidents and jams etc. An increase in the basic level of unforeseen expenses occurs every 500 km by 1%. For example, for a distance between 1000 to 1500 km, unforeseen expenses will be 7% of the total transport OPEX.

Calculation of the LNG unit price, taking into account transportation by trailers, was carried out according to the following formula:

\[
P_{\text{LNG}} = P_{\text{NG}} + \frac{P_{L}}{k_1} + (N_t \cdot P_t \cdot DR_t \cdot Ex_{\text{OP}}^t)/Vol_{ng}
\]  (1)

where \(P_{\text{NG}}\) - price of purchased natural gas from the main pipeline, RUR/m3; \(P_{L}\) - price of liquefaction per ton of LNG, RUR/t; \(k_1\) - coefficient to convert LNG volume to natural gas (1.38026); \(N_t\) - number of trailers; \(P_t\) - price of one trailer, RUR; \(DR_t\) - depreciation rate of trailers; \(Vol_{ng}\) - total volume of LNG in terms of natural gas, m3; \(Ex_{\text{OP}}^t\) - transport OPEX (formula 2).

\[
Ex_{\text{OP}}^t = N_t \cdot N_v \cdot l \cdot P_G \cdot V_t \cdot L + N_d \cdot h \cdot S_d \cdot k_2 + UE_i
\]  (2)

where \(N_t\) - number of voyages per one trailer; \(l\) - the distance between LNG plant and point of destination, km; \(P_G\) - price of gasoline, RUR/liter; \(V_t\) - LNG tank capacity, tons; \(L\) - load rate, %; \(N_d\) - number of drivers, people; \(h\) - working hours in estimated period, hour; \(S_d\) - wage of a driver, RUR/hour; \(k_2\) - coefficient to increase a wage (table 1); \(UE_i\) - unforeseen expenses, RUR.
2.4. Pipeline CAPEX and OPEX

The capacity of a gas pipeline depends on its diameter and the working gas pressure. The determination of the required maximum capacity is based on the need to transport 31,056 million m³ of natural gas (22 500 tons of LNG) per year. Approximate calculations to select the required diameter of a pipe can be performed with a high degree of certainty by formula 3.

\[
D = \sqrt{\frac{Q_{\text{max}}}{0.67 \cdot (p_{\text{work}} + 1.033)}}
\]

where \(Q_{\text{max}}\) – maximum capacity of the gas pipeline, m³/h; \(p_{\text{work}}\) – working gas pressure, MPa.

Gas pipelines construction CAPEX include the cost of compressor stations (CS), the cost of pipes, the cost of laying the pipeline and unforeseen expenses. For the assessment, five possible pipeline diameters were selected, depending on the number of delivery directions. The volume of supplies in each direction decreases in proportion to their total number. Table 2 shows the initial data for analysis.

Gas pipeline OPEX are mainly related to the need to maintain the operation of compressor stations (95% OPEX). Based on the analysis of the existing compressor stations, taking into account the required volume of supplies, the following was accepted:

- for 90 mm diameter, OPEX of one compressor station is 3034.5 th. USD per year;
- for 62 mm - 2827 USD / year;
- for 51 mm - 2621 USD per year;
- for 45 mm - 2414 USD per year;
- for 41 mm - 2206 USD per year.

### Table 2. Basic technical parameters for the pipeline gas price calculation

| Indicator                  | Units          | Number of delivery directions |
|----------------------------|----------------|-------------------------------|
|                            | 1              | 2              | 3              | 4              | 5              |
| Diameter                   | Mm             | 90             | 62             | 51             | 45             | 41             |
| Capacity                   | th.m³/h        | 3.8            | 1.8            | 1.2            | 1.15           | 0.96           |
| Work pressure              | MPa            | 0.6            | 0.6            | 0.6            | 0.75           | 0.75           |
| Distance between CS        | Km             | 160            |                |                |                |                |
| Price of CS                | th. USD        | 20.7           | 13.8           | 10.3           | 8.6            | 5.2            |
| Price of the pipe          | th. USD/km     | 5              | 2.9            | 2.6            | 1.7            | 1.6            |
| Pipeline laying            | th. USD/km     | 18.9           |                |                |                |                |
| Unforeseen expenses        | %              | 10             |                |                |                |                |
| Depreciation rate          | %              | 4              |                |                |                |                |
| OPEX                       | th.USD/km-year | 5.2            | 3.5            | 2.4            | 1.2            | 0.7            |

The cost of pipeline gas was calculated with using the following formula:

\[
P_{\text{PG}} = n \cdot (Ex_{\text{pipe}} + Ex_{cs}) / Vol_{ng}
\]

where \(n\) - number of delivery directions, according to table 2; \(Ex_{\text{pipe}}\) - expenses for a pipeline (formula 5), RUR; \(Ex_{cs}\) - expenses for a CS (formula 6), RUR.

\[
Ex_{\text{pipe}} = l \cdot (1 + UE_{\text{pipe}}) \cdot (Ex_{\text{op} \text{pipe}} + DR_{\text{pipe}} \cdot P_{\text{pipe}})
\]

where \(UE_{\text{pipe}}\) - unforeseen expenses for the construction and operation of the gas pipeline, unit fraction; \(Ex_{\text{op} \text{pipe}}\) - pipeline OPEX, RUR/km per year; \(DR_{\text{pipe}}\) - depreciation rate of a pipeline, unit fraction; \(P_{\text{pipe}}\) - price of the pipe, according to table 2.

\[
Ex_{cs} = N_{cs} \cdot (1 + UE_{cs}) \cdot (Ex_{\text{op} \text{cs}} + DR_{cs} \cdot P_{cs})
\]

where \(N_{cs}\) - number of CS; \(UE_{cs}\) - unforeseen expenses associated with CS, RUR; \(Ex_{\text{op} \text{cs}}\) - CS OPEX, RUR/year; \(DR_{cs}\) - depreciation rate of the CS, unit fraction; \(P_{cs}\) - price of the CS, RUR.

2.5. Proposed technical-economic model

To carry out the assessment, a technical-economic model was developed (Figure 3). This model allows to compare two options for region territory gasification, taking into account the required volume of gas.
supplies and the number of supply routes from the “starting point”. The “starting point” is a place located near the main gas pipeline, where it is possible to build an LNG plant, or to create a branch of a low-capacity gas pipeline to supply several locations with gas. The key technical and economic parameters specified in the model were discussed above.

The proposed model could be divided into 2 parts: Part A. The economic evaluation was carried out on the basis of similar projects analysis. The result of this evaluation is plant’s OPEX (201 USD per ton of LNG) and CAPEX (13.4 mln USD). Part B. Calculations were carried out on the basis of a mathematical model expressed by the formula 7.

\[

def(n,l) \rightarrow def(n_{max},l_{max}) \\
\text{Min}(P_{LNG} \cdot P_{PG}) \\
0 < l \leq l_{max} \\
N_i = N_d \\
L = 1 \\
N_v, N_{vl}, N_{ct}, Vol_{NG} > 0 
\]

2.6. Assumptions and simplifications

Calculations are based on a comparison of the LNG price \(P_{LNG}\), expressed in a similar volume of natural gas in cubic meter, with the price of natural gas transported by a pipeline \(P_{PG}\). The delivery distance \(l\) varies from 1 km to \(l_{max}\), with \(l_{max}=7500\) km. The value \(l_{max}\) is the maximum theoretical distance that one trailer can pass and go back to the plant in one month.

To conduct a comparative assessment of transportation to several locations, the total volume of transported gas was divided by the number of directions \(n\). At the same time, the delivery distance was accepted equal for all directions. For example, transportation in two points at a distance of 1000 km means that 11 250 tons of LNG will be delivered to each point and the distance from the plant to each point is 1000 km.

\(N_i=N_d\) indicates that the number of drivers is equal to the number of trailers, since an excessive increase in the number of employees will lead to a significant increase in total wages, especially with long distance delivery. On the other hand, the lack of drivers will not allow to transport all produced LNG.

\(L=1\) indicates that the loading of each tank is 100%. In other words, for one trip a trailer carries 19 tons of LNG. Thus number of voyages \(N_v\), the number of trailers \(N_t\), the number of CS \(N_{ct}\) and the volume of purchased natural gas \(Vol_{NG}\) must be greater than zero to exclude errors in the calculations.
3. Results
Calculations have shown that the attractiveness of using LNG produced at low-tonnage plants instead of pipeline gas depends on the range and number of supply directions (Figure 4).

![Figure 4. Results of gas price modeling](image)

In general, the result showing that the use of LNG in 1 and 2 directions of supply is more expensive than pipeline gas, does not contradict world practice and is one of the most significant reasons for the predominance of a pipeline transport. However, if we talk about 3 or more directions of supply, which is possible, for example, in the implementation of the regional gas supply strategy, LNG can be considered as a competitor to a pipeline gas (Figure 5).

![Figure 5. Multi-directional delivery distances with equivalent prices](image)

For delivery in 3 directions (Figure 5C) LNG can compete with natural gas at a distance of over 3 845 km. However, the theoretical possibility of such long-distance delivery by trailers does not necessarily mean its implementation. For example, in Russia, such a range of deliveries is possible for transporting LNG from the European part of the country to Siberia, but in most cases, the location of the main gas pipeline allows the use of pipeline gas at a much shorter transportation distance.

However, for delivery in 4 (Figure 5B) and 5 (Figure 5A) directions LNG can compete with pipeline gas at much smaller distances. Given the vast territory of Russia and a large number of small settlements, it is already possible to talk about the possibility of improving the strategic energy supply programs of the regions by using low-tonnage LNG plants. In general, it can be expected that further increase in the number of supply directions, an increase in the efficiency of the gasification process and a decrease in the cost of trailers will lead to increasing in LNG attractiveness at distances of less than 500 km.

4. Conclusion
At present, the development of LNG industry is constrained by high production and transportation costs compared to pipeline gas. This fact is confirmed by significant number of research papers devoted to the evaluation of medium - and large-tonnage LNG production projects, as well as by small number of studies of low-tonnage production, which in most cases do not allow to conduct a fair comparison with pipeline gas. The technological schemes with use of LNG allow to provide a greater flexibility of supply, which makes them more attractive than pipeline transport for supplying several remoted locations.

The relevance of the development of low-tonnage LNG production for the Russian market lies in the possibility of creating schemes for supplying energy resources to sparsely populated areas and remote regions, in which the gas pipeline is unprofitable and inexpedient in a view of the relatively small
volumes of demand for energy raw materials. However, despite the results obtained during the evaluation, for the large-scale implementation of the LNG projects, it is necessary to introduce additional measures of state support to compensate a part of production and transport costs. It can be argued that LNG production plants have good prospects for development in Russia and abroad. However, there are too few research devoted to the solution of problems of low-tonnage LNG production and the prospects of their large-scale implementation. In this regard, further work will be aimed at improving the accuracy and complexity of the model for assessing LNG projects, both in terms of production and transport solutions, and in the use of LNG or regasified gas. This can be of significant practical importance in view of the reorientation of energy markets from petroleum raw materials to natural gas.

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