A Comprehensive Evaluation Method the Effectiveness of the Prospect of Inter-Fuel Competition for the Production of Electric and Thermal Energy in the Arctic Regions of the Republic of Sakha (Yakutia)

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Abstract. The article deals with the methods for assessment of the environmental, energy, and economic efficiency of the liquefied natural gas (LNG) for the production of electrical and heating power in the Arctic regions of the Republic of Sakha (Yakutia). The basic factors for the development of LNG production and supply to the settlements, which are remote from gas pipelines in the Republic of Sakha (Yakutia) (Republic), are identified. The authors reveal the advantages of LNG utilization instead of the actually used traditional types of fuel (coal, crude oil, gas condensate, diesel fuel) for diesel power stations and boiler plants in the Arctic regions of the Republic in the context of inter-fuel competition in the production of electrical and heating power.

The introduced methods for assessment of the environmental, energy, and economic efficiency are substantiated with experimental calculations in terms of the electrical power production at diesel power plants of JSC Sakhaenergo and in heating power production at boiler plants, which belong to several economic structures, mainly to GUP ZhKKh RS (Y), JSC Sakhaenergo, and JSC Teploenergoservice.

As a result, the authors substantiated a method for a comprehensive assessment of LNG effectiveness for the electrical power production at diesel power plants and in heating power production at boiler plants, which are located in 13 Arctic regions of the Republic.

1. Introduction
Reliable and continuous energy supply to the Arctic territories of the Russian Federation is a high priority for the government authorities at all levels. Therefore, it is necessary to analyze the factors that determine the demand for efficient energy resources.

The role of natural gas in the economy and the society of the Republic of Sakha (Yakutia) is significant. Natural gas is used for the production of electrical and heating power in the central and western regions (60%), local businesses and technological operations (29%), and domestic needs (9%). The natural gas consumption for the production of electrical and heating power is more than 50%, despite the inter-fuel competition with local coals (35%) and crude oil (5%).

For many years, the priorities of the regional energy policy have been the availability of industrial and public supply of gas, the transition to the use of environmentally safe fuel (such as natural gas) by
production and communal infrastructures, and the reduction of operating costs for the production of electrical and heating power. In practice, this process is implemented in accordance with the state and departmental investment programs for gas supply to the settlements and production facilities of the Republic of Sakha (Yakutia). The construction of the gas trunkline, The Power of Siberia, for natural gas delivery to the People’s Republic of China (PRC), as well as to adjacent regions, contributes to the importance of natural gas for electrical and heating enterprises.

2. Methodology
Methods for assessment of the efficiency of alternative types of motor fuel have been studied by Tokarev, Karavaikov, Garkushina, Tarasov, Khazin, and Furzikov [1, 2, 5, and 6]. Rachevsky [4] introduced a technical and economic assessment of the production and consumption of liquefied natural gas. The economic efficiency of LNG as an energy source for various facilities in the region was investigated by Fedorov, Byadovskiy, Rudenko, and Demyanov [7]. Fundamental and applied research on the development and expansion of inter-fuel competition in global and regional energy markets have been carried out by Galkina, Mitrova, Elyakova, Khristoforov, Kondratev, Karataeva, Danilova, and Elyakov [3, 8].

Despite the available research results and the developed and substantiated methods for a comprehensive assessment of the LNG in terms of environmental, technological, and organizational efficiency, the use of LNG as fuel (primary energy source) for the production of electrical and heating power (secondary energy resources) is insufficient in some territories of the Arctic zone of the Russian Federation.

The authors implemented the following research methods: general scientific methods (analysis and synthesis); theoretical methods followed by analysis; and generalization of the results (statistical, comparative).

The scientific novelty of this work lies in the development and substantiation of an integrated method for assessing the efficiency of the use of LNG for the production of electrical and thermal energy, taking into account the peculiarities of the ecological, energy and economic efficiency of the Arctic regions of the Republic of Sakha (Yakutia), which is applicable to all Arctic regions of the world with decentralized consumers energy.

3. Results and discussion
In the Republic of Sakha (Yakutia), there is no unified regional gas supply network connected to the main pipeline system for the transportation and supply of gas to consumers in Eastern and Western Siberia. Gas supply zones for consumers in the central and western regions of the Republic are localized and isolated from each other.

Natural gas extraction is carried out by several gas production and transportation companies. The dynamics of the changes in the volume of natural gas production is presented in Figure 1.
According to the research carried out by the specialists of Non-Governmental Research Institute for Industrial Gas Use (VNIIPromgaz), it is economically reasonable to provide about 50% of the settlements, which need gas supply, with imported LNG [1].

The relevance of gas supply for the settlements, which are remote from gas pipelines, as well as the development of LNG production in the Republic of Sakha (Yakutia) are determined by the following factors:
- Throughout the vast territory of the Republic (more than 3.1 million m²), especially in its sparsely-populated remote areas, where there are no industrial enterprises that utilize natural gas in large volumes, the construction of trunk and distribution gas pipelines is technologically and economically unreasonable and unjustified.
- Promising natural gas deposits in the Republic are located in remote, impassable areas and are unfavorable for gas pipeline construction; it is advisable to transport LNG instead.
- LNG is a cryogenic liquid, which is convenient and non-toxic for utilization, storage, and transportation. It must be stored under slight excess pressure at a temperature of about 161 °C in special tanks with thermal layers.
- LNG is environmentally safe in terms of storage; if it is spilled, it evaporates without soil contamination.
- LNG is environmentally-safe fuel for the production of electrical and heating power.
- LNG can be delivered to consumers in any settlement in order to provide gas supply to the facilities, especially in difficult-to-reach areas, which are remote from gas pipelines.
- LNG is effectively applied as a fuel for boiler plants and diesel power plants with gas-diesel generators, as well as motor fuel for river and road transport.
- High heat value (specific heat) compared to other types of boiler and furnace fuel, which justifies the efficiency of its utilization.
- Lower cost compared to alternative types of traditional fuel (coal, fuel oil, diesel fuel, gas condensate).
The possibility of technological optimization of diesel power plants for the utilization of diesel fuel, natural and liquefied natural gas; power plants refit to operate on LNG purely (approximate payback time for gas equipment is from two to six months [2]).

Energy efficiency, which is determined by significantly low price for LNG comparing to the equivalent diesel fuel in terms of heating value.

The price for LNG is lower in comparison with imported diesel fuel, when it is produced on the territory of the Republic and transported to consumers.

It is necessary to build low-tonnage plants for LNG production in the areas of promising deposits; although, their construction is most effective near gas pipelines in the cities with the largest volumes of natural gas consumption, transport hubs (federal railways and highways crossing, river ports for the delivery to consumers), where transport infrastructure is developed, and proper labor potential is available.

According to the investigation of the structure of the fuel utilization for heating power production in the Arctic regions of the Republic of Sakha (Yakutia) in 2020, the share of coal is 62%, crude oil is 29%, gas condensate fuel is 8%, and diesel fuel is 0.04% (Table 1, Figure 1).

Table 1. The structure of the fuel utilization for heating power production in the Arctic regions of the Republic of Sakha (Yakutia) in 2020.

| Indicator | coal | oil | gas condensate | diesel fuel | Total |
|-----------|------|-----|----------------|-------------|-------|
| t.s.f.    | 160k | 75k | 21k            | 112         | 257k  |
| %         | 62%  | 29% | 8%             | 0%          | 100%  |

$t.s.f.$ – tonne of Standard Fuel

It can be concluded that coal is essential fuel for heating power production, although it contaminates the atmosphere with CO2, which is the most harmful emission, as well as with ash and soot.

The production of LNG includes its transit (transportation), storage, regasification (use in a liquid state), and distribution to consumers, i.e. boiler and diesel power plants at the remote Arctic regions of the Republic of Sakha (Yakutia). In addition, the facilities for electric and heating power production should be upgraded or built in order to use a new type of fuel, such as LNG. Therefore, technological and industrial preparation of consumers, transport infrastructure (river, sea, and road transport), and rational logistics schemes for the delivery, storage, and distribution of LNG should be provided.

It is worth emphasizing the economic, environmental, organizational, and energy efficiency of inter-fuel competition in terms of the substitution of traditional types of fuel for the alternative type / types.

The authors introduce the method for environmental efficiency assessment through the indicators, which make it possible to calculate regular environmental damage in the Arctic regions of the Republic of Sakha (Yakutia) by means of the following Formula:

\[ E_{env.} = E_{real\ env.\ safety} = E_{harm} = V_{pol.\ em.} \times P_{co2} = RDH \]  \hspace{1cm} (1)

Where:
- $E_{real\ env.\ safety}$ is Real Environmental Safety,
- $E_{harm}$ is Probable Cost of the Harm done for people and the environment,
- $V_{pol.\ em.}$ is Volume of Polluting Emissions, tones,
- $P_{co2}$ is CO2 price, rubles per t.s.f.,
- $RDH$ is Regularly Done Harm to the environment, rubles.
- $E_{env.} = 2,994.1$ million rubles (Table 2).
Table 2. Calculation of the ecological efficiency of LNG application for the production of electrical and heating power in the Arctic regions of the Republic of Sakha (Yakutia).

| Fuel type       | 2020     | 2021     | Emission reduction effect | The cost of reducing emissions |
|-----------------|----------|----------|---------------------------|-------------------------------|
|                 | Fuel volume | CO₂ emissions | Cost of emissions at CO₂ price = 2,681 rubles per ton | Fuel volume | CO₂ emissions | Cost of emissions at CO₂ price = 2,681 rubles per ton |
|                 | Thou sand t.s.f. | Thousand tons per year | Million rubles | Thou sand t.s.f. | Thousand tons per year | Million rubles | Thou sand t.s.f. | Thousand tons per year | Million rubles |
| Coal            | 160.1    | 347.5    | 931.5                     |                 |                      |                  |                 |                      |                  |
| Oil             | 75.2     | 902.9    | 2419.1                    |                 |                      |                  |                 |                      |                  |
| Gas Condensate  | 21.9     | 45.0     | 120.5                     |                 |                      |                  |                 |                      |                  |
| LNG             |          |          |                           | 257.3           | 422.8               | 1133.6           |                 |                      |                  |
| Total           | 257.2    | 1295.4   | 3471.1                    | 257.3           | 422.8               | 1133.6           | 872.6           | 2337.5               |
| For heating power production |         |          |                           |                 |                      |                  |                 |                      |                  |
| Diesel Fuel     | 86.2     | 177.3    | 128.2                     | 86.2            | 141.7               | 102.4            |                 |                      |                  |
| LNG             | 343.5    | 1472.7   | 1064.8                    | 343.6           | 564.5               | 408.1            | 908.2           | 656.6               |
| SUBTOTAL        |          |          |                           |                 |                      |                  |                 |                      |                  |

Subscript – tonne of Standard Fuel

Energy efficiency can be estimated through Energy Efficiency Coefficient of a boiler in the Arctic regions of the Republic of Sakha (Yakutia) by the following Formula:

\[ E_{\text{erg}} = V_{\text{tp prod}} \times 142.86 \times \text{Conv.coef.fuel} \times \text{Price fuel} \]  \hspace{1cm} (2)

Where:

- \( V_{\text{tp prod}} \) is Heating Power Production, (142.86 kg of oil equivalent is required to produce 1 Gcal), 142.86 is specific standard fuel consumption,
- Efficiency Coefficient of a boiler
- \( \text{Conv.coef.fuel} \) is Conversion Coefficients of Fuel types in terms of heating value,
- \( \text{Price fuel} \) is the Price per ton of natural Fuel.

The energy efficiency of the primary energy source in comparison with LNG can be estimated through the overall boiler efficiency (Table 3).
Table 3. Calculation of the energy efficiency of the primary energy source in comparison with LNG through the overall boiler efficiency in the Arctic regions of the Republic of Sakha (Yakutia).

| Indicators                        | Unit of measure | Coal     | Oil     | Gas Condensate | LNG     |
|-----------------------------------|-----------------|----------|---------|----------------|---------|
| Efficiency Coefficient of a boiler| %               | 55       | 65      | 70             | 85      |
| Production                        | Gcal            | 100      | 100     | 100            | 100     |
| specific standard fuel consumption| Kg sf per Gcal  | 259.7    | 219.8   | 204.1          | 168.1   |
| Standard Fuel Consumption         | t.s.f.          | 26.0     | 22.0    | 20.4           | 16.8    |
| Conversion Coefficient            | coef.           | 1.24     | 0.71    | 0.69           | 0.82    |
| Fuel Consumption on Heat Production| t.n.f.         | 32.3     | 15.6    | 14.1           | 13.8    |
| Fuel price per ton                | Rubles per t.n.f.| 12200    | 46500   | 39900          | 19800   |
| Fuel costs                        | Thousand rubles | 393.9    | 725.6   | 561.9          | 274.2   |
| Heating Power Production, 2021    | Thousand Gcal   | 703.8    | 561.3   | 142.3          | 1408.8  |
| Fuel price per ton                | Rubles per t.n.f.| 12200    | 46500   | 39900          | 19800   |
| Fuel costs                        | million rubles  | 2772.2   | 4073.1  | 799.7          | 3863.0  |
| Fuel Cost Saving                  | million rubles  |          |         |                | 3782.0  |

\[ t.n.f. \text{ – tonne of Natural Fuel} \]
\[ t.s.f. \text{ – tonne of Standard Fuel} \]

Calculations of the energy efficiency of traditional fuels in comparison with alternative fuel, such as LNG, which were carried out according to Formula 2, made it possible to determine production indicators by means of the total boiler efficiency in the Arctic regions of the Republic of Sakha (Yakutia) (Table 3). As a result, specific standard fuel consumption, standard fuel (SF) consumption, and, consequently, the consumption of natural fuel for the production of heating power with LNG is less than for all the traditionally used types of fuel in the Arctic regions of the Republic. The cost indicators of LNG utilization defined significant savings in natural fuel costs (for 3782.0 million rubles).

The method of cost-effectiveness can be calculated through Formula 3:

\[ E_{\text{econ}} = C_f - C_{\text{lng}} = (P_f \times V_f) - (P_{\text{lng}} \times V_{\text{lng}}) \]  

(3)

Where:
\[ E_{\text{econ}} \] is Cost-Effectiveness Indicator,
\[ C_f, C_{\text{lng}} \] are Fuel Costs and LNG costs, rubles,
\[ P_f, P_{\text{lng}} \] are Fuel Price and LNG Price, rubles per t.s.f.,
\[ V_f, V_{\text{lng}} \] are Fuel Consumption and LNG Consumption, t.s.f.

a) for calculating the cost savings indicator to substitute diesel fuel (DF) with LNG in each Arctic region of the Republic of Sakha (Yakutia):
- to produce electricity at Diesel Power Plants (DPP),
- to produce heating power at boiler plants, using coal, crude oil, gas condensate, and diesel fuel;

b) payback time for advanced LNG projects:
- for heating energy production is 10 years,
- for electrical energy production is 2 months.

The calculation of the expected economic efficiency of DF substitution with LNG for electrical power (EP) production in the Arctic regions of the Republic of Sakha (Yakutia) for 2021 is introduced in Table 4.

**Table 4.** The calculation of the expected economic efficiency of LNG for electrical power production in the Arctic regions of the Republic of Sakha (Yakutia).

| Districts                | EP Production kWh | DF Consumption t.n.f. | LNG Consumption t.n.f. | SF Consumption kWh | DF price per t.s.f. million rubles | LNG price per t.s.f. million rubles | Price Variations per t.s.f. million rubles | DF costs milli. rubles | LNG costs milli. rubles | Saving milli. rubles |
|--------------------------|-------------------|------------------------|------------------------|-------------------|-------------------------------------|--------------------------------------|---------------------------------------------|-----------------------|-----------------------|----------------------|
| Abyisky district         | 12.7              | 3363                   | 3 105                  | 4 876             | 42.1                                | 12.6                                 | 29.5                                        | 205.4                 | 61.5                  | 143.9                |
| Allaikhovsky District    | 10.2              | 2642                   | 2 440                  | 3 830             | 44.3                                | 14.4                                 | 29.9                                        | 169.6                 | 55.3                  | 114.3                |
| Anabarsky District       | 12.7              | 3318                   | 3 065                  | 4 812             | 43.9                                | 15.1                                 | 28.7                                        | 211.0                 | 72.7                  | 138.3                |
| Bulunsky District        | 37.2              | 9020                   | 8 331                  | 13 079            | 40.7                                | 14.0                                 | 26.7                                        | 531.8                 | 182.9                 | 348.9                |
| Verkhnechelymsky District| 20.5              | 5297                   | 4 892                  | 7 681             | 47.9                                | 14.8                                 | 33.1                                        | 368.2                 | 113.8                 | 254.4                |
| Verkhoysky District      | 33.8              | 9390                   | 8 672                  | 13 615            | 50.1                                | 17.7                                 | 32.4                                        | 682.5                 | 241.5                 | 441.1                |
| Zhigansky District       | 14.2              | 3655                   | 3 376                  | 5 300             | 39.0                                | 13.4                                 | 25.6                                        | 206.9                 | 71.0                  | 135.9                |
| Momsky District          | 11.5              | 3281                   | 3 030                  | 4 758             | 52.1                                | 25.8                                 | 26.2                                        | 247.7                 | 122.9                 | 124.9                |
| Nizhnekolymsky district  | 5.4               | 1925                   | 1 778                  | 2 791             | 46.7                                | 15.5                                 | 31.2                                        | 130.3                 | 43.2                  | 87.2                 |
| Olenyoksky District      | 12.0              | 3341                   | 3 086                  | 4 845             | 43.5                                | 19.4                                 | 24.1                                        | 210.8                 | 93.8                  | 117.0                |
| Srednekolymsky District  | 19.7              | 5310                   | 4 904                  | 7 699             | 47.8                                | 14.2                                 | 33.6                                        | 367.8                 | 109.0                 | 258.7                |
| Ust-Yansky District      | 35.3              | 7445                   | 6 876                  | 10 795            | 46.6                                | 15.9                                 | 30.7                                        | 503.6                 | 172.1                 | 331.5                |
| Eveno-Bytantaysky District| 5.4               | 1492                   | 1 378                  | 2 163             | 51.3                                | 18.2                                 | 33.1                                        | 110.9                 | 39.4                  | 71.5                 |
| SUBTOTAL                 | 231               | 59478                  | 54932                  | 86244            | 45.8                                | 16.2                                 | 29.6                                        | 3946                  | 1379                  | 2567                 |
The expected economic efficiency of LNG for electrical power production in the Arctic regions of the Republic of Sakha (Yakutia) is 2567 million rubles.

The calculation of the expected economic efficiency of LNG for heating power (HP) production in the Arctic regions of the Republic of Sakha (Yakutia) for 2021 is introduced in Table 5.

**Table 5.** The calculation of the expected economic efficiency of LNG for heating power (HP) production in the Arctic regions of the Republic of Sakha (Yakutia).

| Districts                  | Heat Power Production | Fuel Consumption | SF Consumption | LNG Consumption for HP Production | Aver age price of 1 t.s.f. | LNG Price Variations per 1 t.s.f. | Fuel costs (coal, oil, gas condensate) | LNG costs | Fuel Cost SAVING | LNG Cost Saving, excepting 4 districts |
|----------------------------|-----------------------|------------------|----------------|-----------------------------------|---------------------------|------------------------------------|----------------------------------------|-----------|-----------------|----------------------------------------|
|                            | Coal | oil | gas condensate | thousand Gcal | Thous and t.n.f. | Thous and t.n.f. | Thous and t.n.f. | Thous and t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. | mil lion rubles per t.s.f. |
| Abyisky district           | 100.0 | 15.0 | 3.4 | 10.3 | 16.1 | 27.7 | 12.6 | 15.1 | 446.1 | 203.3 | 242.7 | 242.7 |
| Allaikovsky District       | 68.1 | 7.7 | 7.0 | 7.0 | 11.0 | 31.1 | 21.3 | 9.8 | 340.3 | 233.0 | 107.3 | 107.3 |
| Anabarsky District         | 69.9 | 8.2 | 7.4 | 7.4 | 11.7 | 27.1 | 21.6 | 5.5 | 315.6 | 251.5 | 64.1 | 64.1 |
| Bulunsky District          | 156.0 | 14.1 | 3.0 | 15.6 | 24.5 | 27.2 | 20.6 | 6.6 | 665.8 | 505.3 | 160.5 | 160.5 |
| Verkhinekolynsky District  | 105.2 | 25.1 | 12.0 | 18.9 | 5.8 | 21.0 | -15.2 | 108.9 | 396.7 | -287.8 |
| Verkhoyansky District      | 202.3 | 61.2 | 29.3 | 46.0 | 31.9 | 23.6 | 8.4 | 1468.3 | 1083.4 | 385.0 | 385.0 |
| Zhigansky District         | 81.7 | 20.0 | 0.4 | 9.9 | 15.6 | 7.3 | 23.6 | -16.3 | 113.7 | 367.2 | -253.5 |
| Momsky District            | 105.6 | 7.4 | 10.2 | 12.8 | 20.1 | 28.9 | 23.4 | 5.5 | 581.1 | 470.4 | 110.6 | 110.6 |
| Nizhnekolymsky district    | 91.3 | 19.4 | 1.4 | 10.5 | 16.5 | 14.1 | 23.6 | -9.4 | 233.0 | 388.5 | -155.5 |
| Olenyovsky District        | 82.8 | 0.0 | 5.6 | 4.2 | 8.9 | 14.0 | 28.7 | 23.3 | 5.5 | 400.9 | 324.5 | 76.4 | 76.4 |
| Srednekolymsky District    | 150.8 | 32.6 | 0.5 | 16.1 | 25.2 | 11.6 | 23.9 | -12.3 | 293.0 | 603.3 | -310.4 |
| Ust-Yansky District        | 154.8 | 32.5 | 4.8 | 19.9 | 31.2 | 23.7 | 21.4 | 2.3 | 741.4 | 668.7 | 72.7 | 72.7 |
| Eveno-Bytantaysky District | 40.2 | 4.7 | 4.2 | 6.7 | 48.5 | 23.6 | 24.9 | 323.5 | 157.1 | 166.3 | 166.3 |
| SUBTOTAL                   | 1408 | 213 | 52.6 | 15.3 | 164 | 257 | 24.1 | 21.8 | 2.3 | 6031 | 5653 | 378 | 1385 |

*t.s.f. – tonne of Standard Fuel  
t.n.f. – tonne of Natural Fuel*
According to the calculations of the efficiency of LNG for heating power production in the Arctic regions of the Republic of Sakha (Yakutia), the Fuel Cost Saving is 1385 million rubles.

The expected economic efficiency of LNG for electrical and heating power production in the Arctic regions of the Republic of Sakha (Yakutia) is 3952 million rubles.

The calculation of indicators for a comprehensive assessment of the LNG efficiency compared to other types of fuel (crude oil, coal, firewood) for the production of heating and electrical power has been introduced and carried out, and can be presented by the following formula:

\[ \text{IE lng} = \text{E env} + + \text{E econ} \]  

Where:
- \( \text{IE lng} \) is integrated efficiency indicator of LNG utilization,
- \( \text{E env} \), \( \text{E econ} \) are indicators of environmental and economic efficiency,

\( \text{E enrg} \) is energy efficiency is included into the calculation of the economic efficiency indicator.

In value terms, the total energy and environmental effect of traditional fuel substitution with LNG is \((2337.5 + 3952.0) = 6289.5\) million rubles.

4. Conclusions

The application of environmentally-safe fuel, such as LNG, for heat and power plants (boiler plants) in the Arctic regions of the Republic of Sakha (Yakutia) is important for the environment, especially for the fragile ecosystem of the Arctic, taking into account the negative consequences of the Greenhouse Effect, caused by CO2 emissions, as well as for a favorable living and the population’s health maintenance.

The total expected economic efficiency of LNG for the production of electrical and heating power in the Arctic regions of the Republic of Sakha (Yakutia) is 6289.5 million rubles.

Implementation of the projects for the construction of LNG production plants, terminals for its shipment, reception and storage, technological preparation of diesel power plants for LNG utilization (re-equipment or technological optimization of power generation systems of diesel power plants) contributes to the increase of energy, environmental and economic efficiency due to operating costs (fuel costs). In addition, the population, as well as industrial and social facilities of the northern region will be provided with reliable and continuous energy supply.

It is strategically important to have a unified system of regional gas pipeline united into the Russian unified gas pipeline system in order to ensure the energy security of gas supply to life-supporting facilities and life-sustaining activity of the population.

According to the results of the study, the authors point out the integrated efficiency and strategic importance of LNG for the production of electrical and heating power in the Arctic regions of the Republic of Sakha (Yakutia), alongside with renewable energy sources and nuclear energy.

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