Assessment of the global climate change impact on Fuel and Energy Complex infrastructure and adaptation opportunities in the Russian Arctic

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Abstract. The paper considers the problems and features of the functioning of the energy complex in the regions of the Russian Arctic under the influence of global climate change. Particular attention is paid to new ideas and developments intended for practical use in developing measures to adapt to the adverse effects of climate change. The issues of optimising the composition and structure of the energy economy of the Arctic territories in the areas of permanent residence, reducing the burden on natural ecosystems, and risks in the field of sustainable economic and social development of the Arctic region are discussed. The ways are proposed for developing new approaches to the formation of a strategy for the development of the region’s energy infrastructure under the influence of climatic and environmental factors on the natural environment. The mechanisms of the impact of changes in the climatic characteristics of the region on the operating conditions and the efficiency of energy facilities of the fuel and energy complex are determined. The degree of this dependence was studied for different types of infrastructure facilities of the fuel and energy complex. The data on the assessment of the impact of global climate change on the infrastructure of the fuel and energy complex and the possibilities for its adaptation, which include: the implications for power generation facilities; impact on energy transportation; problems of thawing permafrost and solifluction; climate impact on energy consumption and socio-economic effects; the role of distributed energy and renewable energy in adaptation to climate change. It is shown that for the territories of the Russian Arctic with isolated energy supply, the development of energy-efficient systems and renewable energy will reduce climate risks for sustainable growth. Not only of this power sector but the whole economic complex of the region due to both their better adaptation to the effects of climate change and the reduction of technogenic greenhouse gas emissions, which are one of the main factors of these changes.

1. Introduction

Climatic conditions of the Arctic region are largely determined by the amount of advective heat brought by ocean currents and air currents from low geographical latitudes. The radiation balance at high latitudes is predominantly negative, and the temperature regime is determined mainly by the ability of the atmosphere to interfere with the thermal radiation of incoming advective heat into space [1]. As a result, climatic conditions are formed in the Arctic with freezing winters in the north of...
Siberia, and a milder climate in the north of the European part of Russia. Relatively mild climatic conditions in the north of the European part of the Arctic determined the active industrial and economic development of the region, the development of minerals, the formation of large urban agglomerations, the creation of a developed energy infrastructure that provides economic activity, electricity and heat supply to the industrial and domestic sectors. Thermal power plants prevail in the electricity generation sector, and boiler houses play a significant role in ensuring heat supply. The network of power lines provides power to most settlements. The proportion of isolated consumers is negligible. In the Siberian sector of the Arctic with extreme climatic conditions (low temperatures, strong gusty winds, the presence of ice cover in the waters of the Arctic seas), resettlement is mainly focal with the formation of cities and large settlements and areas of mining, oil and gas production. The energy infrastructure is predominantly represented by thermal power plants in populated areas, gas turbine stations in places of mining, and diesel generators in small towns. The electricity transmission sector is practically undeveloped due to the high cost of building power lines in extreme climatic conditions on permafrost thawing in the summer. On existing power transmission lines, it is necessary to monitor the state with the help of devices over the tendency of possible icing of wires and take measures in the form of installing wind turbines that counteract the formation of ice. This method of protection has already been successfully applied in Russia on Sakhalin.

The creation of new energy infrastructure facilities due to the high ecological “vulnerability” of the natural landscapes of the Arctic requires preliminary studies to assess the environmental impact with particular care. Non-compliance with ecological requirements and standards may become an insurmountable obstacle to the creation of new energy facilities and power lines. The development of wind energy in the Russian Arctic requires mandatory preliminary monitoring of migration routes of migratory birds and coordination with ornithological centres. It is necessary to install individual systems for cleaning emissions from coal-fired boiler plants and thermal power plants, with a gradual decrease in their share in the energy balance of the region and a gradual transition to gas turbine plants and gas boiler plants.

Particular attention is required to energy infrastructure projects in protected areas. In the Arctic zone of the Russian Federation (AZRF), specially protected natural territories (SPNA) of national and regional significance occupy 13.7% of the area (5.3% of federally protected areas, and 8.4% of local importance), which is significantly higher than the average in Russia [2]. Currently, within the borders of the Russian part of the Arctic, there are 21 specially protected natural territories of national significance with a total area of more than 27 million hectares. It includes the marine area of about 10 million hectares. Currently, there are 12 state reserves in the Russian Arctic. The Wrangel Island Nature Reserve is a UNESCO World Heritage Site. The reserves "Big Arctic", "Vodlozersky", "Lapland", "Central Siberian" and "Taimyr" have an international biosphere status.

To protect the nature of the Arctic, environmental legislation will be improved. It is planned to develop environmental quality standards, ensure control over their implementation, introduce monitoring of the anthropogenic and technogenic impact on the natural environment of the Arctic regions. A special regime of nature management and the introduction of a strict system of environmental restrictions, rules and regulations is necessary [3]. These measures will contribute to the creation in the region of renewable energy power plants (RES), gas turbine stations and low-power nuclear power plants as more environmentally friendly. Therefore, it increases the cost of building traditional hydrocarbon power plants, especially on coal, as well as the use of diesel generators in protected areas [4,5].

2. The impact of climate change in the Russian Arctic on the development of energy infrastructure

Global climate transformations that have taken place over the past decades are also evident in the Arctic region. An increase in temperature and an increase in precipitation give grounds for several researchers to predict significant changes in climatic and natural conditions in the Arctic [6–8].
The program for the development of the Arctic zone of the Russian Federation is an essential component of the long-term planning of the country's socio-economic development. One of the defining moments of the successful implementation of the Program is the creation of energy infrastructure for sustainable energy supply throughout the Arctic region for an extended period. That is why it is necessary to consider and evaluate the impact of possible long-term climate changes on the development of the energy complex in the region. The main features of the energy infrastructure of the Russian Arctic are the structure of the population, mining and production facilities on the territory with the remote location of settlements, the almost complete absence of transport infrastructure, especially in the eastern part of the Arctic, extreme weather conditions in winter.

The most significant natural changes for socio-economic development of the region associated with an increase in atmospheric temperature are - decrease in the area of ice cover in the seas of the Arctic Ocean, intensification of degradation processes in permafrost, changes in the wind and precipitation regimes, increase in the ocean level, causing a shift in the location of the edge sea waters, intensification of abrasive processes in the coastal zone, as well as the shift of boundaries of natural zones in the north [9,10]. Mathematical modelling of changes in key climate parameters in the Arctic region showed that the impact of global warming on the Russian part of the Arctic would be heterogeneous: in general, temperatures will rise almost everywhere, in the Asian region they will increase much more. Similarly, the amount of precipitation in the Russian Eastern Arctic will increase more significantly than in the North of the European part of the country. Most of all, the amount of rain falling in winter, which is also the layer of snow cover, will increase: by the end of the century for the Yamalo-Nenets Autonomous Okrug - by 40%, and for the north of Yakutia and Chukotka - by 70% [11].

According to Roshydromet, over the past 40 years, the average annual temperature in the Arctic zone in Russia has increased by an average of 2 °C, and winters have become warmer by 3-4 °C. In other seasons, the temperature increased by 1–1.5 °C. The total rainfall has not changed. If we talk about data for the last ten years, then the increase in average annual temperature in the whole territory of Russia averaged 0.45 °C, i.e. more than 2.5 times larger than the global one, with up to 0.8 °C in the Arctic zone of Russia [12]. Several scientists consider an increase in the temperature of atmospheric air as a result of cyclical fluctuations in atmospheric processes [13].

Changes in climatic characteristics inevitably affect both operating conditions and the efficiency of energy facilities, while the degree of dependence for different types of power plants varies significantly [14].

2.1. The impact of climate change on energy generation power

The safety of thermal and nuclear plants is significantly affected by changes in extreme values of temperature and humidity, wind speed, and the frequency of tornadoes, which can cause significant damage to structures, and calm, since calm conditions increase the concentration of harmful impurities in the air [15]. Extreme tornadoes are especially dangerous for nuclear facilities since they can cause a fuel leak accident. When designing a nuclear power plant, the condition for safe operation is the probability of exposure to tornadoes of less than 0.01%. For TPPs, the increase in average annual temperatures and the associated reduction in heating costs and the relative decline in energy costs for generating capacities are definite. However, sharp changes in air temperature, typical of intensive climate changes, hurt the efficiency of gas turbine plants: an increase in the average annual temperature of 5 °C reduces the ability of a gas turbine thermal power plant by 1.5-2.5%. [14]. Probable warming and increased precipitation will not lead to accidents at nuclear power plants since the adopted degree of protection are very high. However, with an increase in the frequency of occurrence and intensity of natural hazards, the degree of threat can be changed (only three degrees are dangerous for infrastructure facilities, as well as for a complex of buildings and structures that use nuclear or radiation-hazardous technologies. At the same time, the greatest threat to nuclear power plants and they're the environment, taking into account their localisation in the Murmansk Region and Chukotka is represented by storms and hurricanes [16].
With changing climatic conditions, the hydropower potential and the operating conditions of hydroelectric stations in a specific area can change their value. Of highest importance for hydropower is the climate-related change in river flow. A decrease in the flow of water into the reservoir of a hydroelectric power station leads to a reduction in the production of hydroelectric power, and an increase in the current intensifies the generation of energy. However, extremely high values of water inflow can lead to floods and failure of hydroelectric power units [17, 18]. In the Russian Arctic, hydroelectric power plants play a significant role now in the Murmansk region. With the installed capacity of hydro turbines at hydroelectric power stations, electricity generation at existing hydroelectric power stations will remain stable. However, during periods of particularly wet years, there will be a need for more frequent releases of water from hydraulic structures bypassing turbines, to avoid catastrophic rises in the water level in reservoirs. In general, the Arctic region is expected to see an increased rate of spring flood runoff by 23% and decrease its coefficient of variation by 14% according to overall averaging scenarios of climate change [19, 20].

2.2. Influence on energy transportation

Energy transmission is carried out mainly through power lines. The most significant climatic characteristics for power lines are the maximum ice-wind and wind loads, as well as the number of days with dangerous weather events (thunderstorm, hail, rainfall, snowfall). Also, high air temperatures are hazardous because they lead to tensile wires. In this case, their sagging and contact with neighbouring wires are possible, causing a short circuit. Climate warming leads to an increase in extreme atmospheric loads and the need to increase the cost of construction and maintenance of power lines. Frequent increases in air temperature in winter and an increase in the number of cases of liquid precipitation, including supercooled rain, will lead to an increase in the risks of dangerous icing and accidents on power lines (wire breaks and destruction of poles). Accidents on power lines are terrible not so much because of the need to restore them. The cost of restoration work can range from 2-3 million to 10 million rubles. However, the main danger is that the entire region is disconnected from a power supply, including compressor stations on the main pipelines, many of which do not have autonomous power supply [16].

2.3. Problems of thawing permafrost and solifluction

Climate change causes an increase in the temperature of permafrost soils, a decrease in their strength properties and the intensification of a number of destructive geocryological processes, such as thermokarst, solifluction, uneven subsidence of the soil, etc. When thawing soil, methane and carbon dioxide are evolved from it, which were recorded by permafrost. The release of these gases can change the balance of carbon dioxide in the Arctic as a whole, which means that global warming will go even faster. For the Russian Arctic, this effect is hazardous since more than 80% of the territory is located on the permafrost soils, and 45% of the urban population of the Arctic lives in the zone of distribution of frozen soils [21]. The warming and degradation of permafrost have already contributed to the widespread deformation of technical and building structures in several settlements, in particular in Norilsk. In recent years, the number of structures that suffered damage due to uneven subsidence of foundations has increased compared to the previous decade in Norilsk by 42%, Yakutsk - by 61%, Anderme - by 90%. Developments are needed to solve specific geotechnical problems of man and climate associated with permafrost, and innovative, cost-effective solutions for safe infrastructure construction [22]. Forecasts indicate that these changes will intensify over the next several decades, as a result of which the risks of damage and destruction of structures and transport communications in the permafrost zone arise and increase over time [23].

Improving the safety level of the construction of energy infrastructure facilities on permafrost soils (MMG) under climatic changes requires increasing the safety factor in order to maintain the stability of structures even in areas with relatively “weak” MMGs. As a result, the foundation will be able to perform its functions at higher soil temperatures. Such an increase in the safety factor will lead to a
a significant increase in the cost of construction of extensive power facilities (nuclear power plants, thermal power plants, hydroelectric power stations) [23].

2.4. **Consumption of electric and heat energy**

The impact of climate on electricity consumption is expressed, first of all, in the fact that it is the climatic conditions that largely determine the level of energy demand. Consequently, climate change can significantly affect energy consumption in the Russian Arctic. An essential aspect of the impact of climate change on the energy sector is the reduction of heat energy needs, especially in winter. Warming will shorten the duration of the heating season. It is estimated that the Arctic zone of the European part of Russia will decrease its length by 40–50 days a year by the middle of the 21st century and by 60–70 days a year by its end. The total cost of the heating season here may fall by 30%. In arctic conditions, this is especially important because in several regions of the Russian North, energy systems are isolated and their operation depends on a costly northern delivery. Reducing the need for imported fuel can mitigate this problem. One of the most critical tasks is to refine estimates of the expected duration and temperature of the heating period, as well as such climatic indicators as heat deficit and severe deficit in the regions of Russia [16].

Considering the possible impact of climate change in the Russian Arctic on the development of energy infrastructure in the region, we can talk about both negative and positive aspects in economic terms. An increase in average annual temperature values, moreover, mainly due to winter warming, will lead to a reduction in thermal energy consumption in the Arctic due to a decrease in the duration and temperature regime of the heating period, and, accordingly, will result in significant savings in heat supply. On Figure 1 presents the authors' calculations to reduce the duration of the heating season in the cities and towns of the Russian Arctic by 2050 compared to 2015 (according to [24]). These evaluations may serve as a basis for forecasting and planning the reconstruction of the heat supply system in the region.

![Figure 1. Forecast for a reduction in the duration of the heating period 2050/2015, degree-day, % (with an average street temperature of less than 8 °C and a room temperature of 22 °C). Source: Authors' calculations; [24].](image-url)

Prediction of energy consumption by the population of the Russian Arctic is based on data on the structure of its distribution over the territory, and migration flows and abundance. At the present stage, there is a sharp "contraction" of the urbanised and industrial space of the Russian Arctic.

A large share of the urban population and the associated production potential is shifting east to oil and gas production areas - to permafrost distribution zones with increasing risks of its degradation. According to the forecast studies, in the future, the share of the population of the Siberian Arctic will...
increase due to the gradual outflow of the northern community of the European part and an increase in migration towards large oil projects [21]. Following these trends, the restructuring of the fuel and energy complex infrastructure will take place.

2.5. Distributed energy and the role of renewable energy in the development of the energy infrastructure of the Russian Arctic

With low populated areas of the Russian Arctic, the presence of a large number of local consumers, the development of distributed energy is proposed as the most promising option for distributed power development [25].

The boundaries of economically feasible electricity transmission through power lines networks is depending on the connected load (1-5 MW), and usually in the range of 25-75 km with electricity tariffs of 9-12 Rub. / kWh [26]. At higher taxes, these distances can be higher, but they are, as a rule, still less than the distances to the nearest large energy nodes. Therefore, connection to centralised energy supply systems is, in most cases, impossible. One of the main directions of the development of energy infrastructure in the Russian Arctic is the development of distributed energy for the decentralised energy supply of isolated consumers. The global market for distributed energy technologies (small distributed generation, demand management, storage, energy efficiency, etc.) is growing at a rate of about 6-9% per year. It is expected that by 2025 the volume of commissioned capacity of distributed generation will exceed the amount of commissioned centralised production by three times. According to the International Energy Agency, distributed energy will provide up to 75% of new connections during global electrification until 2030 [27].

Many types of research are aimed at developing the formation of distributed energy systems using innovative types of electricity production: gas turbine plants, renewable energy facilities, low power nuclear plants [28]. Due to the increasing influence of climate change, the intensification of the development of distributed energy in the Russian Arctic to a power supply of isolated consumers requires research on the event of a methodology for accounting for climate risks [29].

An analysis of the low-carbon energy sources state and prospects of using conducted showed that current tariffs for electricity and heat supply from fossil fuels in the Russian Arctic are significantly reduced. Economically sound taxes are multiple higher. According to the "Center for the Effective Use of Energy" (http://www.cenef.ru), heat tariffs for the population are only 8-19% of economically feasible levels, which vary between 8.6 and 16.9 thousand. Rub / Gcal. A comparison of the economic characteristics of the use of imported fossil fuels at the real cost and the development of renewable energy resources, suggests the prospect of their full inclusion in the Arctic energy complex to reduce emissions of CO₂ and other greenhouse gases in the region [30]. The use of renewable energy technologies can become one of the most important elements of adaptation to climatic changes in the energy infrastructure of the Russian Arctic. The development of Arctic renewable energy is hampered by several factors, mainly related to the harsh climatic conditions of the Arctic. Despite this, the potential of renewable energy sources in the Russian Arctic is significant. The combined use of renewable energy with diesel and gas engine generators in the conditions of decentralised energy supply of the Russian Arctic allows for high reliability of power supply, significant savings due to less use of hydrocarbon fuel [31].

3. Recommendations on adapting the energy infrastructure of the Russian Arctic to changing climatic and environmental conditions

The following are recommendations on some measures to adapt to climate change in the most climate-sensitive sectors of the economy of the Russian Arctic: resource mining and fuel and energy. The recommendations are prepared to take into account the results of the analysis of predicted climate changes and socio-economic characteristics of the region.

Consideration of risks during climate change is critical in the sectors of extraction of fuel resources, production of electricity and heat, and transport of energy resources in the Russian Arctic to minimise the resulting losses from possible threats [32, 33]. The authors summarised and systematised the main
risks in the fuel and energy complex of the Russian Arctic, related to global warming, and also identified several adaptation measures to reduce these risks (Table 1).

**Table 1.** Possible risks threats by climate changes and adaptation measures to them in the fuel and energy complex of the Russian Arctic Zone.

| Sectors                                | Risks Threats                                                                                                                                                                                                 | Adaptation measures                                                                                                                                 |
|----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Extraction of fossil fuel resources    | 1. Increase in the number of accidents involving the equipment of offshore oil production facilities on the Arctic shelf due to sudden changes in temperature and increased winds and other dangerous hydrometeorological phenomena.  
2. Risk of danger growth to mining facilities and vehicles due to an increase of the height of wind waves, the appearance of iceberg debris on the Arctic islands  
3. Increase in the degree of geocryological hazard for engineering structures in the areas of fossil fuel extraction. | 1. Clarification of changes forecasts of climatic parameters up to 2050 and further — the creation of special ice hazard control services in the sea areas of the Russian Arctic.  
2. Development of new technical samples and experimental models of equipment for the extraction of hydrocarbon fuel on the sea shelf.  
3. Consideration of wave height dynamics, ice activity in the design of oil platforms and other structures, ensuring their safe operation.  
4. Conducting research and clarifying the degree of geocryological risk in gas and oil production areas in the Russian Arctic. |
| Heat and electricity production        | 1. The occurrence of increased risks during the operation of buildings of power plants, boiler houses, heat supply systems of industrial and communal buildings up to their destruction due to soil movements in permafrost thawing zones.  
2. Violation of the energy, transport and port infrastructure of coastal areas due to natural anomalies, increased storm activity, coastal erosion, sea-level rise.  
3. Growth of windfarms emergencies due to increased intensity and frequency of hurricane winds. | 1. Development and implementation of innovative technologies, technical norms and regulations by the construction of energy infrastructure facilities for the production of heat and electricity suitable for use in new conditions  
2. Regular updating of geocryological risk assessments for the energy infrastructure facilities in the Arctic region.  
3. In the case of a high degree of destruction threats, reconstruct or transfer energy objects from the danger zone. |
Transport of fuel and electricity

1. Violation of transport links for the traffic of fuel, including maritime shipping, due to an increase in the frequency and intensity of abnormal weather events.
2. Increase in the probability of the complex and dangerous ice conditions on the Northern Sea Route.
3. Growth of the degree of geocryological hazard during the constructing and operating of power lines, trunk pipelines, etc.
4. Reduction in the routes and period for fuel delivering (foil, diesel fuel, coal) to inaccessible areas along winter roads laid along frozen channels due to changes in the timing and processes of freezing and opening rivers and ponds.

1. Improvement of modern systems of prognostic support for marine activities, monitoring the dynamics of hydrometeorological characteristics. Creation of effective local systems of hydrometeorological support and control of the geocryological situation.
2. Creation and operation of reinforced ice-class vessels for the implementation of large offshore gas transportation projects.
3. Improving the quality of monitoring and forecasting hydrological and ice conditions, their climate-related changes in rivers and water bodies of the North.
4. Improvement of the system for promptly reporting weather and climate information to representatives of the energy sector and consumers.

All sectors of the multi-stage production process in the fuel and energy complex (extraction, transportation and processing of fuel, energy production, its transmission and consumption) are dependent on the characteristics of the "weather and climate". By designing of power stations the climatic parameters (extreme values of air temperature, precipitation, the repeatability of the number of days with strong winds, heavy precipitation, thunder, etc.) must be taken into account; the constructing of Wind towers is limited by indicators of wind strength, rainfall, thunderstorms; the calculation of energy consumption is carried out taking into account the outdoor temperature and illumination, etc.

The observed tendency of the variability of climatic characteristics causes the load on the energy complex objects. The moral and physical deterioration of the leading equipment, the exhaustion of the transmission line capacity and the lack of redundancy only increase climate risks.

On the other hand, a change in climatic conditions creates new opportunities, in particular, an increase in hydro- and wind energy potential. It expands the prospects for the use of solar and photovoltaic energy. This emphasises the need to diversify energy sources, develop renewable energy, improve supply and demand management and a power system that can cope with more pronounced fluctuations in demand for electricity.

An essential element of adaptation is the formation of smart grids of distributed energy in the regions of the Russian Arctic. As part of this approach, it will be necessary to create local networks (Microgrid) in places of compact resettlement and separate installations for hydrocarbon fuels or renewable energy sources (with duplication of diesel or gas generating units) for isolated consumers. One of the main adaptation problems associated with the use of renewable energy sources, which Smartgrid should solve, is the problem of stability of power generation.

The adaptation strategy in the fuel and energy complex of the Russian Arctic should be based on the results of studies of long-term changes in the main hydrometeorological parameters. The new energy-efficient technologies, the development of renewable energy sources will help solve the problems of adapting and mitigating the effects of climate change through the greenhouse gas emissions-reducing and energy consumption standards revising in industry and utilities, which can also be considered as an integrated approach to solving the problem of climate change.

4. Conclusion

Climatic changes in the Russian Arctic are increasingly becoming the cause of various natural disasters. These are floods caused by changes in the hydrological regime of rivers, destruction of
buildings and power transmission towers due to the activation of thermokarst processes and solifluction.

Changes in climatic characteristics inevitably affect operating conditions and the efficiency of different types of power facilities. The data obtained in this work of assessing the consequences of the impact of global climate change on the fuel and energy complex infrastructure and the possibilities for its adaptation include five main elements:

- the impact on power generation facilities;
- implications for energy transportation;
- problems of thawing permafrost and solifluction;
- climate impact on energy consumption and socio-economic impacts;
- the role of distributed energy and renewable energy in adaptation to climate change.

Complicated climatic conditions with the high importance of the Russian Arctic for the development of the whole country, lead to the need for an in-depth study of inherent risks and potential damage from natural hazards. The development of energy-efficient systems and renewable energy sources will reduce climatic risks in the territories of the Russian Arctic with isolated energy supply and will contribute to the sustainable growth of both the energy sector and the entire economic complex of the region due to their better adaptation to the effects of climate change and reduction of technogenic greenhouse gas emissions.

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