

Low-power nuclear power plants in the context of electric power systems transformation^{*}

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Abstract

Increasing economic importance of the Arctic, further intensification of northern sea routes, and exceptional sensitivity of the arctic natural environment to anthropogenic impacts are fundamental factors for a comprehensive study of environmental aspects in the application of innovative technologies for the development of infrastructure in the Arctic.

Despite the growing interest in low-power nuclear power plants as a distributed generation facility, their possible application in technologically isolated power systems does not lose relevance. The development of both the Arctic and Far Eastern regions of the Russian Federation presents great opportunities and demand for the use of nuclear power sources. Also, development programs for the Russian arctic zone imply a significant increase in the role and number of nuclear power facilities, in other words of potential radiation-hazardous facilities.

Large-scale use of nuclear-powered installations in the Arctic necessitates advanced development of a scientifically grounded and modern forecasting system as well as assessments of threats and risks in case of possible radiation emergencies at nuclear- and radiation-hazardous facilities. Also, the development of proposals for necessary measures to minimize negative consequences of such emergencies is required. This is especially true for the case of compact placement of industrial, infrastructure and residential facilities in the Arctic in the immediate vicinity of nuclear facilities.

The paper demonstrates that the demand for low-power nuclear power plants and their competitiveness will grow steadily in the conditions of electric-power industry decentralization, further spread of distributed generation and the development of technologically isolated power systems. Approaches to the generation of a low nuclear-power system based on the philosophy of industrialization of production and centralized management are presented. Special features of the environmental impact assessment of low-power nuclear power plants for the development of a methodology to study the radio-ecological hazard related problems are provided.

Keywords

Arctic region, Isolation Power System, Distributed Generation, Low-Power Nuclear Power Plant, Development Forecast, Radiation Safety, Sea Areas, Mathematical Modeling

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Introduction

Low-Power Nuclear Power Plants (LPNPPs) were traditionally intended for use in technologically isolated power systems. In remote regions of the Russian Federation such as the Arctic and the Far East, due to prevalence of decentralized power systems and severe climatic conditions requiring the use of environment-independent power sources autonomous LPNPPs may become a non-alternative basic option for power generation. Since the beginning of the 21st century, countries with a developed nuclear industry (the USA, Canada and Argentina) have been considering Small Modular Reactors (SMR) as promising facilities of distributed generation, which are integral elements of ‘smart energy’ (Sarkisov 2011, 2015). In foreign practice, the term SMR is used for low-power nuclear power sources, but in fact SMRs are a core part of LPNPPs. Below in this article, the terms LPNPP and SMR are considered identical.

Since 2018, there has been an increase in the development, licensing and construction of LPNPPs. In the town of Pevek, the world’s first Floating Nuclear Power Plant (FNPP) ‘*Akademik Lomonosov*’ was put into commercial operation. In Russia, the USA and China preliminary sites for LPNPPs were identified (based on the RITM-200, NuScale and ACP-100 reactor installations, respectively), and licensing procedures are underway; commissioning of pilot plants is scheduled for 2027–2030. The US Department of Energy has initiated ‘*The Advanced Reactor Demonstration Program*’ which will provide \$ 160 million. Simultaneously, the US Department of Defense is implementing ‘*The Pele Project*’ with a budget of about \$40 million for competitive design of three nuclear micro-reactors with a capacity of 1–5 MW - one of them will be selected in 2022 for practical implementation (Advanced Reactor Demonstration Program, Project “Pele”).

Both decentralization and development of distributed generation are a current trend that has the greatest impact on the power industry (Strategy for Digital Transformation, Energy Strategy of the Russian Federation, An Action Plan (“Roadmap”). Facilities of distributed generation are power sources connected to the distribution network and / or those located directly at the power consumer (GOST 58092.1-2018; Preliminary National Standard of the Russian Federation). Thus, in order for LPNPP to comply with the requirements of power system decentralization, the following two conditions must be met:

- installed capacity of LPNPP should be related to levels of consumption within the electric power micro-grid that may be achieved by modular arrangement of LPNPP (discrete power gain); and
- safety requirements for LPNPP should allow them to be placed in close proximity to the consumer, in the distribution network.

On the other hand, when developing basic provisions of new architecture of electric power systems, LPNPP

capabilities and competitive advantages should also be taken into account, such as:

- mobility and modularity of the structure;
- independence from logistics and fuel-storage infrastructure;
- minimal construction-and-installation work at the site;
- independence of power generation from external climatic factors; and
- minimal environmental impact and simplified de-commissioning procedures.

Also, as applied to nuclear power plants, the terms ‘*a small-generation facility*’ and ‘*a distributed-generation facility*’ should not limit the installed capacity to 25 MW. Otherwise, some LPNPP projects (e.g. those based on the RITM-200 reactor installation) may be excluded from the architecture of the Internet of Energy. At present, in accordance with the status of ‘*a wholesale market entity*’ - determined by the Federal Law No. 35-FZ of March 26, 2003 ‘*On Electric Power Industry*’ - this restriction has a widespread though not yet formal use (Preliminary National Standard of the Russian Federation).

Prospects for LPNPP use in the Arctic region of Russia

Despite the growing interest in LPNPP as a facility of distributed generation, their use in technologically isolated power systems does not lose relevance. Further development of the Arctic and Far East regions of the Russian Federation presents great opportunities and demand for the use of nuclear power sources. Since the beginning of the 2000s, information about more than 20 potential sites for LPNPP emplacement in these regions may be found in published sources.

In accordance with the basic public documents regulating the development of both electric power industry and the Arctic region (Energy Strategy of the Russian Federation, Fundamentals of the State Policy of the Russian, Infrastructure Development Plan), civil application of nuclear-power technologies in the Russian Arctic is associated with:

- development of year-round safe navigation along the Northern Sea Route (construction of nuclear icebreakers of a new generation and commercial ice-class fleet); and
- development of both transport-and-social infrastructure and deposits of mineral resources (updating of power supply systems and application of power installations with enhanced operational characteristics to ensure a reliable power supply).

For the Arctic region of Russia, the following categories of power-supply facilities are taken into consideration: transportable modular LPNPPs; nuclear

thermal power plants; underwater LPNPPs for power supply of offshore oil-and-gas production complexes; and maintenance-free nuclear power sources using direct energy-conversion technologies.

Certainly, to optimize the cost of construction and the site accessibility for maintenance and research personnel, the first in their class LPNPPs should be emplaced in centralized power-supply areas. Expansion of LPNPPs into the Arctic region where their economic competitiveness is expectedly higher (Sarkisov et al. 2018a, b; NEA No. 7213 2016) would be advisable only after practicing their construction-and-operation technologies ‘on the mainland’ and setting up serial production of LPNPP modules.

Prospects for the use of nuclear-power technologies in the Arctic region updated on the basis of Refs. (Infrastructure Development Plan, Sarkisov et al. 2018a, Small Modular Nuclear Power Plants) and industry media are summarized in Table 1.

The establishment of a LPNPP system is possible both on the basis of current developments and through designing new LPNPPs unified by power range, which meet the trends in power-system transformation addressed above. Both approaches require an audit of current research & development as well as the generation of a concept for LPNPP system in the Russian Federation. The development of this concept should include the following main milestones:

1. Identification of potential emplacements for transportable and stationary LPNPPs (distributed generation, centralized energy system, and isolated power systems).
2. Analysis of possible operational and design data on power- and heat-supply systems of potential LPNPP sites. Identification of basic parameters - designation requirements (logistics, autonomy, power delivery, and electricity cost) for LPNPPs oriented to domestic use.
3. Assessment of the export potential of LPNPPs. Identification of basic parameters - designation requirements for export-oriented LPNPPs.

4. Elaboration of criteria for LPNPP modular layout and transportability in accordance with basic parameters - designation requirements of Milestones 2 and 3.
5. Elaboration of criteria for centralized serial production of transportable LPNPPs and assessment of industrial potential.
6. Elaboration of criteria for centralized handling of transportable LPNPP modules (including refueling life-cycle stages, handling of radwaste and Spent Nuclear Fuel (SNF), and decommissioning).
7. Multi-criteria analysis (cost, characteristics, and maturity of technology) of existing domestic LPNPP projects for a comparative assessment of their development options in the following segments:
 - up to 5 MW inclusive (including direct-conversion energy sources);
 - from 5 to 50 MW inclusive; and
 - from 50 to 300 MW.
8. Determination of LPNPP unified appearance in terms of power performance, transportability and autonomy of operation in accordance with the criteria of Milestones 2-6.
9. Preliminary justification of nuclear and radiation safety of unified LPNPPs.
10. Analysis of existing experimental facilities (reactor benches, production and technological facilities for fuel testing and manufacture) and the need for their upgrading and further development.
11. Development of a ‘roadmap’ for designing an experimental and prototype model of a unified LPNPP including cooperation of enterprises for project implementation.
12. Evaluation of unified LPNPP construction cost, and development of an economic life-cycle model.
13. Development of proposals on regulatory-and-legal framework to be developed for the generation of a LPNPP system.

Table 1. Reactor installations operated (or planned for operation) in the Arctic region

RI type	Reactor Installations (RI) in operation			Thermal power, MW	Facility
	2020 (as of June)	2030 (conservative scenario*)	2030 (optimistic scenario*)		
OK-900A	4	2	2	171	‘Yamal’ and ‘50 Years of Victory’ nuclear icebreakers
KLT-40M	2	0	0	171	‘Vaigach’ and ‘Taimyr’ nuclear icebreakers
KLT-40	1	0	0	135	‘Sevmorput’ lighter carrier
RITM-200	0	6	10+2	175	Construction of a main and 4 serial nuclear universal icebreakers of design 22220 + LPNPP
RITM-200B	0	0	1	209	Offshore nuclear icebreaker
RITM-400	0	2	4+2	315	Construction of a main and 1 serial nuclear icebreaker of ‘Leader’ design + arctic-class nuclear container ships
KLT-40C	2	2	4	150	FNPP
ABV-6M	0	0	1–2	38	LPNPP
Shelf				28	
Megawatt class RI	0	0	1–2	3–6	
Total RI in operation	9	12	27–29	–	–

* authors’ assessment.

Safety of LPNPP use in the Arctic

In accordance with Ref. (Fundamentals of Public Policy of the Russian Federation in the Arctic for the period up to 2035), among major challenges of environmental protection and environmental safety are:

- continuation of elimination of accumulated harm to the environment; and
- implementation of a variety of measures to prevent toxic and radioactive substances as well as pathogens of infectious diseases from being released into the Russian Arctic.

As part of the research on predicting environmental impact in the event of emergency at nuclear floating facilities, LPNPPs are considered among most promising power facilities for the Arctic region. Comprehensive modeling of the spread of radionuclides in various media (air, water) is being carried out, and recommendations for taking measures to minimize negative implications of emergencies for the population and the environment are being developed.

Large-scale application of nuclear installations in the Arctic region requires a scientifically based and modern system of forecasts and assessments of threats and risks in the event of a radiation emergency at nuclear- and radiation-hazardous facilities. Also, the development of proposals for taking adequate measures to minimize negative implications of such emergencies is required. This is especially true for the case of compact emplacement of industrial, infrastructure and residential facilities in the Arctic when LPNPP construction is planned in close proximity to the consumer. National nuclear regulatory authorities of leading nuclear countries have been already considering the possibility of reducing LPNPP controlled areas and supervised areas.

For further research of radio-ecological problems in the Russian Arctic zone in order to enhance radiation and environmental safety of human beings and the environment under conditions of intense use of offshore and onshore nuclear-powered facilities some representative LPNPP emplacements were identified as of the time of this writing. Promising sites were selected based on the following criteria: analysis of electrical loads of existing and prospective consumers in the Russian Arctic region, and publications about pilot LPNPP sites in open sources (Sarkisov 2015; Small Modular Nuclear Power Plants, Sarkisov et al. 2018b; Saneev et al. 2020) – Table 2.

In accordance with the IAEA recommendations, when justifying and developing a methodology of studying radio-ecological hazards, the following features of the Environmental Impact Assessment (EIA) should be taken into consideration as applied to LPNPPs (IAEA-TEC-DOC-1915 2020; Naumov et al. 2018):

- readiness and time of response to emergency situations taking into account remoteness and transport accessibility of LPNPP sites;

Table 2. Prospective offshore and onshore LPNPP emplacements in the Arctic region

Emplacement	Prospective electrical loads
Novaya Zemlya Archipelago (the Barents Sea), Bezymyannaya bay	Development of the Pavlovskoye lead-zinc deposit
A hypothetical oil platform in the Barents or Kara Sea	Exploration and production drilling, oil production
The port of Dickson	Reconstruction and expansion of the port of Dickson and its transport-and-social infrastructure; development of coking coal deposit
The port of Tiksi	Reconstruction and expansion of the port of Tiksi and its transport-and-social infrastructure
The town of Pevek, Chukotka Autonomous District	Expansion of the Chaun-Bilibino energy center for the development of deposits of mineral resources. Replacement of the FNPP during its overhaul.

- duration of LPNPP fuel lifetime. Extending the fuel life cycle to 5–7 years would significantly reduce SNF amount to be stored at LPNPP site as well as the frequency of delivery and the amount of new fuel; at the same time, the activity of produced fission products would increase in such a case;
- refueling of some LPNPPs is expected by replacement of the entire non-defueled reactor vessel that would reduce the likelihood of emergencies during refueling;
- a LPNPP contains less nuclear fuel than a high-power reactor installation. When simulating emergency situations with a release of radionuclides, their amount may be scaled by the ratio of the reactor's thermal power (Table 1) taking into account the comparability of fuel lifetime duration;
- enrichment of nuclear fuel. When using nuclear fuel of similar enrichment at high-power NPPs, isotopic composition of fuel is expected to be the same in the first approximation; and
- structural shape of the fuel matrix, which prevents significant emissions of fission products.

Conclusions

The demand for Low-Power Nuclear Power Plants (LPNPPs) and their competitiveness will grow steadily in the conditions of electric-power industry decentralization, further spread of distributed generation and the development of technologically isolated power systems.

The designing of LPNPPs is based on a new philosophy of nuclear power application and firstly is related to both industrialization of their production and development of a technology for centralized SNF and radwaste management.

The development of a LPNPP system is possible using both existing audited technologies and completely new LPNPP developments based on the principles of series production, modular design, maximum autonomy, centralized handling and safe emplacement in the vicinity of the consumer.

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