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RUSSIAN EXPERIENCE IN IMPLEMENTING DIGITAL TECHNOLOGIES IN NUCLEAR ENERGY

Artur S. Kostanov [1]

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A B S T R A C T

The research presents a systemic analysis of Russia's experience in implementing digital technologies in the nuclear power industry. The research examines strategic directions of digitalization, ongoing projects, and specific examples of practical application of advanced IT solutions at nuclear energy facilities. Special attention is paid to the development of digital twins, predictive analytics systems, artificial intelligence, and cybersecurity and import substitution issues. The author describes the economic and technological effects achieved through digital transformation and outlines prospects for further development of digital solutions in the Russian nuclear energy sector. This research was completed as part of the master's graduate qualification work. The research was carried out under the scientific supervision of Candidate of Economics, Associate Professor, T. A. Mustafin, Department of the World Economy, Diplomatic Academy of the Russian Foreign Ministry.

1. INTRODUCTION

The digital transformation of industrial sectors is an objective necessity for contemporary technological development. Russia's nuclear energy industry, a strategically important sector of the national economy, is actively integrating advanced digital solutions into the design, construction, and operation of nuclear facilities. Rosatom State Corporation is a pioneer in industrial digitalization, implementing a large-scale program to introduce information technology to improve operational efficiency, ensure safety, and strengthen competitiveness in the international market (Nuclear Energy 2.0, 2025).

Digitalization of the nuclear industry addresses a range of pressing issues, such as improving the accuracy of equipment performance monitoring, reducing the impact of human error, optimizing technological processes, and creating the conditions for predictive maintenance. Given the increasing demands for energy security and the need for import substitution in critical technologies, Russia's experience in the digital transformation of the nuclear energy sector is particularly relevant (Lalovich, 2019; Vybornykh et al., 2023).

The research aims to systemically analyze the practical results of implementing digital technologies in the Russian nuclear energy sector, identify key development areas, and evaluate the achieved results. The scientific novelty of this work lies in its comprehensive examination of Russia's experience in digitalizing the nuclear industry, based on current data and specific examples of completed projects.

[1] Corresponding author: Artur S. Kostanov
Email: artur.kostanov1743@gmail.com

2. LITERATURE REVIEW

The presented research is based on a study of a body of scientific publications by Russian and international researchers relevant to the research objectives. Specifically, the author reviewed the works of Dunaev and Medvedovsky (2013), Degtyareva and Murzintseva (2021), and Kharitonov and Semenova (2023), which contain various approaches to identifying the most promising digital technologies for implementation in nuclear energy.

Concurrently, some authors, including Lalovich (2019), Vybornykh et al. (2023), and De los Angeles Renteria del Toro et al. (2024), examine the factors necessary for the development of digital infrastructure for nuclear energy, ranging from the creation of a regulatory framework to the development of a personnel training and cybersecurity system.

Comparing the findings of these scientific papers with current information from official publications and press releases from authorized executive bodies of the Russian Federation, the State Corporation Rosatom, and its subordinate structures makes it possible to clarify the current state of the industry and track the progress of digitalization projects.

3. METHODOLOGY

In preparing this research, the author employed a comprehensive methodological approach, combining universal and empirical methods of scientific inquiry. This approach made it possible to fully explore key aspects of the digitalization of Russia's nuclear energy sector using the State Atomic Energy Corporation Rosatom as an example. Thus, the use of observation and description allowed the author to identify key technologies for the digitalization of Russia's nuclear energy sector and articulate their significance for the sector's strategic development. Furthermore, the use of analytical and abstraction methods provided a basis for systematizing the accumulated data, which subsequently made it possible to model the potential economic and technological impacts of implementing nuclear energy digitalization policies on the Russian economy.

4. RESULTS

Rosatom State Corporation's unified digital strategy, approved in 2018, the first of its kind among Russian state corporations, set out the core principles guiding the industry's technological transformation. The strategic vision through 2030 aims to achieve full digital maturity across all of the corporation's business products and to increase digital revenue tenfold. (Degtyareva & Murzintseva, 2021).

The implementation of more than 60 projects as part of creating a unified digital platform includes the migration of the electronic document management system to an independent platform, the implementation of the "Digital Rosatom" ERP system on a fully Russian technology stack, and the deployment of the industry-specific messenger Atom Space. These solutions form an integrated ecosystem of IT tools, ensuring seamless operation across all segments of the nuclear industry (TAdviser, 2025). Advanced automatic control and monitoring systems for nuclear power plants (NPPs) are high-tech systems that automate technological processes and monitor the operating parameters of power units (Tripoten, 2025). The TPTS software and hardware developed by VNIIA are certified by Rostekhnadzor for use at Russian NPPs and boast a mean time between failures (MTBF) of over 70 million hours (DigitalRosatom, 2025). The integrated use of the TPTS-NT and TPTS-SB systems supports the development of comprehensive automation solutions for nuclear and thermal power plants. The high technical performance of this equipment enables the processing of several thousand signals within millisecond-level observation cycles, which is an essential capability for ensuring nuclear reactor safety (DigitalRosatom, 2025).

Another promising area is NPP digital twins. They represent a virtual model of the equipment, systems, and processes of a nuclear power plant at various stages of its lifecycle. Russian developers are creating software and hardware systems that enable the connection of a digital twin to a real facility through a system of sensors and information infrastructure, collecting and processing operational information in real time (Dunaev & Medvedovsky, 2013). A pilot project to create a digital 3D model of Unit 6 with a VVER-1200 reactor has been implemented at the Novovoronezh NPP. It encompasses 360 process systems of a nuclear power unit and includes 157 interactive procedures (Rosatom Service, 2024). The economic impact of implementing a fully-fledged digital twin, considering the 70–100-year operational life of a nuclear power plant, is estimated at hundreds of billions of rubles.

Furthermore, a predictive analytics system (PAS) developed by VNIIAES has been implemented in trial operation at Unit 4 of the Beloyarsk NPP. The system analyzes information from several thousand sensors installed on key process equipment, including the turbogenerator, turbine, and various types of pumps. To detect and predict changes in process parameters, the system uses machine learning and statistical data analysis methods (Leaders of Russia, 2024). Under normal operating conditions, the system analyzes the equipment's status every five minutes, increasing the frequency to once per second during transient states. Data sets are processed in real time at the data center, enabling the prediction of the time remaining before the equipment reaches its operational limits and the localization of any detected deviations.

Information technologies help reduce the risk of error in analyzing important NPP operating parameters by 25% (Pirogova, 2023). Russian specialists are actively exploring the use of artificial intelligence for monitoring and diagnostics, as well as its integration into automated

process control systems (Siberian Branch of the Russian Academy of Sciences, 2020). Machine vision systems improve the accuracy of crack and defect detection in reactors. The development of AI technologies expands the potential for robotic applications in hazardous areas (Nosov, 2016; VNIIA Rosatom, n.d.).

At the Novovoronezh NPP, the development of an operator information support system (OISS) has begun with the participation of RASU and IF SNIIP ATOM (Rosatom Service, 2024). This system represents the first step toward creating digital backups for operating personnel, using AI technologies for predictive modeling of nuclear facility design, operation, and modernization processes.

Ensuring the cybersecurity of digital technologies is a critical challenge for the nuclear power industry (Forbes, 2024). Russian nuclear power plants employ a five-layer cybersecurity architecture, with the automated process control system (APCS) located in an isolated network, disconnected from the Internet. The first circuit includes sensors and software logic controllers. The second circuit includes gateway equipment for collecting and processing information.

Atomenergoproekt, together with Kaspersky Lab, has developed a comprehensive cybersecurity plan for NPPs with VVER-1200 reactors, covering all types of computerized systems and comprising more than 140 technical documents. The risk assessment methodology is based on international standards of the IAEA and the International Electrotechnical Commission (DigitalRosatom, 2024; Liou, 2024).

Russia has also made a significant leap forward in the global quantum race, creating working quantum computers on all four priority platforms: ions, atoms, photons, and superconductors (TAdviser, 2021, 2025). Only three countries have achieved such feats: the USA, China, and Russia. As part of the roadmap, a 50-qubit ion-based quantum computer and a 50-qubit atom-based quantum computer have been created (Nuclear Energy 2.0, 2020). The Rosatom State Corporation has allocated 12 billion rubles for the development of quantum computing between 2020 and 2024 (Country Rosatom, 2022, 2023). Russian physicists have demonstrated the quality of inter-qubit operations at 95% for a two-qubit system, significantly exceeding the initial target of 60% (Country Rosatom, 2024). Digital transformation helps address labor shortages, improve productivity, reduce production costs, and shorten production lead times (AtomMedia, 2025; De los Angeles Renteria del Toro et al., 2024). Investments in digitalization for next-generation reactors can reach 3% to 23% of capital expenditures, assuming a 60%–80% reduction in overall capital expenditures. The implementation of the Internet of Things is projected to generate $1.3 trillion in total revenue for the nuclear sector by 2025 (E2nergy, 2023). The Industrial Internet of Things (IoT) has the potential to add between $3.9 and $11.1 trillion to the global economy each year, with approximately $80 billion generated by the electric power sector.

In 2022, up to 80% of Russian production facilities used foreign digital products. The government has set a goal of achieving complete import independence for entire classes of industrial software by 2030 (Pirogova, 2023). Rosenergoatom has launched a global import substitution program, covering over 150 components previously purchased abroad (Energy Land, 2024; Kharitonov & Semenova, 2023). The Rostov Nuclear Power Plant has begun manufacturing components using a renovated centralized repair shop with a modernized machine tool fleet. The creation of a thermal processing facility allows for the full cycle of manufacturing and machining components for the repair of thermal-mechanical equipment directly on-site (Energy Land, 2024).

Russian experience in implementing digital technologies in the nuclear energy sector demonstrates a systems-based approach to the technological transformation of the industry. The implementation of the Unified Digital Strategy of the Rosatom State Corporation has ensured the creation of an integrated ecosystem of digital solutions covering all aspects of the nuclear industry, from the design to the operation of nuclear facilities.

5. DISCUSSION

This research builds on the studies by Dunaev and Medvedovsky (2013), Degtyareva and Murzintseva (2021), and Kharitonov and Semenova (2023), contributing to the development of the scientific concept of nuclear energy digitalization. It expands this concept by providing an in-depth analysis of advanced digital technologies that can enhance energy security in the Russian nuclear sector and support the future export growth of Russian nuclear technologies.

Supporting the findings of Lalovich (2019), this research found that digitalization and optimization of operations will help overcome increased economic pressure on the nuclear industry, thereby improving operational efficiency and ensuring long-term sustainability in the sector.

Building on the findings of De los Angeles Renteria del Toro et al. (2024), this research confirms that advanced technologies in the nuclear energy sector possess substantial export potential and could become a strategically significant component of Russia's export portfolio. In line with the conclusions of Vybornykh et al. (2023), this research provides a comprehensive analysis of Russia's experience in nuclear industry digitalization, identifies key areas for the development of digital technologies in nuclear energy, and evaluates the outcomes achieved through specific implementation cases by the State Corporation Rosatom.

6. CONCLUSION

Key achievements include the implementation of predictive analytics systems, the development of digital

twin technologies, the creation of world-class quantum computers, and the enhancement of cybersecurity for critical infrastructure. The economic benefits of digitalization encompass increased operational efficiency, reduced risks, and optimized production processes.

The strategic importance of Russia's experience lies in fostering technological sovereignty and establishing a foundation for exporting digital solutions to international markets. According to Rosatom State Corporation's Digital Vision 2030, Russian digital technologies are expected to be utilized in at least 30 countries.

Development prospects include scaling up successful practices, deepening the integration of artificial intelligence into production processes, and expanding the application of quantum technologies. The Russian nuclear industry continues to consolidate its position as a global leader in industrial digitalization, laying the groundwork for sustainable technological growth amid modern challenges.

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Artur S. Kostanov
Diplomatic Academy of the
Ministry for the Foreign Affairs
of Russia, Moscow, Russia
artur.kostanov1743@gmail.com
ORCID: 0009-0008-2304-4969