The North African Journal of Scientific Publishing (NAJSP)
مجلة شمال إفريقيا للنشر العلمي (NAJSP)
E-ISSN: 2959-4820
Volume 3, Issue 2, 2025
Page No: 183-194
Website: https://najsp.com/index.php/home/index

SJIFactor 2024: 5.49 | **معامل التأثير العربي (AIF) 2024: 0.71** | **ISI 2024: 0.696**

Artificial Intelligence in Nuclear Power Plants: A Comprehensive Review of Applications and Challenges

Wisam Algsaier[1*], Gebriel Gannat[2]
[1,2] Department of Electronic Engineering, College of Industrial Technology, Misurata, Libya

الذكاء الاصطناعي في محطات الطاقة النووية: مراجعة شاملة للتطبيقات والتحديات

وسام القصير[1*]، جبريل جنات[2]
[1,2] قسم الهندسة الإلكترونية، الكلية التقنية الصناعية، مصراتة، ليبيا

*Corresponding author: wisamelgsaier@gmail.com

Received: April 08, 2025	Accepted: June 05, 2025	Published: June 16, 2025

Abstract:
Thanks to AI, Nuclear Power Plants (NPPs) can improve safety, efficiency and better predict maintenance, thanks to AI. Then, the review provides an analysis of both AI applications and the issues that arise when deploying AI at nuclear plants. To begin, the study explains what AI is, outlines main concepts of AI, rational and cognitive thinking and describes how AI is being applied in intelligent automation. The role of AI in NPPs is further highlighted by examining its contributions to finding faults, detecting anomalies, ensuring NPP safety and making fast decisions during operations. This report concentrates on the use of AI in nuclear power systems, mainly via machine learning improvements and looks at the history of digital equipment in these operations. The conversation covers implementing AI-supported mobile computing in nuclear power stations, outlining the setup for AI in mobile devices, why private cloud is crucial for supporting AI apps and what the future can offer because of IoT, AI and Blockchain. Even though AI can help, there are many problems associated with introducing it to nuclear settings, for example, meeting regulations, cooperating with human workers, defending against cyberattacks, being able to afford it and educating the personnel who will use it. The article demonstrates that strong laws, interaction between experts and progress in AI openness and safety are required to make nuclear energy more secure.

Keywords: Artificial Intelligence, Nuclear Power Plants, Machine Learning, Digital Technologies, Mobile Computing, Internet of Things.

الملخص
بفضل الذكاء الاصطناعي، يُمكن لمحطات الطاقة النووية تحسين السلامة والكفاءة والتنبؤ بالصيانة بشكل أفضل. ثم تُقدم المراجعة تحليلاً لتطبيقات الذكاء الاصطناعي والقضايا التي تنشأ عند نشره في المحطات النووية. في البداية، تشرح الدراسة ماهية الذكاء الاصطناعي، وتُحدد المفاهيم الرئيسية للذكاء الاصطناعي، والتفكير العقلاني والمعرفي، وتصف كيفية تطبيقه في الأتمتة الذكية. كما يُسلّط الضوء على دور الذكاء الاصطناعي في محطات الطاقة النووية من خلال دراسة مساهماته في اكتشاف الأعطال، واكتشاف الشذوذ، وضمان سلامة محطات الطاقة النووية، واتخاذ قرارات سريعة أثناء التشغيل. يُركز هذا التقرير على استخدام الذكاء الاصطناعي في أنظمة الطاقة النووية، لا سيما من خلال تحسينات التعلم الآلي، ويتناول تاريخ المعدات الرقمية في هذه العمليات. يغطي النقاش تطبيق الحوسبة المتنقلة المدعومة بالذكاء الاصطناعي في محطات الطاقة النووية، ويُحدد إعدادات الذكاء الاصطناعي في الأجهزة المحمولة، ولماذا تُعدّ السحابة الخاصة ضرورية لدعم تطبيقات الذكاء الاصطناعي، وما يُمكن أن يُقدمه المستقبل بفضل إنترنت الأشياء والذكاء الاصطناعي وسلسلة الكتل. على الرغم من قدرة الذكاء الاصطناعي على المساعدة، إلا أن هناك العديد من التحديات المرتبطة بتطبيقه في البيئات النووية، مثل الالتزام باللوائح، والتعاون مع العاملين، والحماية من الهجمات الإلكترونية، والقدرة على تحمل تكلفته، وتثقيف

الموظفين الذين سيستخدمونه. يوضح التقرير أن القوانين الصارمة، والتفاعل بين الخبراء، والتقدم في انفتاح الذكاء الاصطناعي وسلامته، كلها عوامل ضرورية لجعل الطاقة النووية أكثر أمانًا.

الكلمات المفتاحية: الذكاء الاصطناعي، محطات الطاقة النووية، التعلم الآلي، التقنيات الرقمية، الحوسبة المتنقلة، إنترنت الأشياء.

Introduction

By 2025, the worldwide nuclear power sector consisting of almost 420 operating reactors is on track to produce more electricity than at any other time [1]. Even as some countries are phasing out their nuclear plants, overall nuclear power production is on the rise due to important developments in the sector. In Japan, reactors have been brought back online, France completed important upgrades and new generators are now operating in China, India, Korea and several European countries [1,2]. Nuclear power provides almost 10% of the world's electricity, putting it in second place for low-emission energy after hydropower. The rise in the need for clean, steady and large-scale power solutions has maintained nuclear energy's important part in decarbonizing worldwide power generation.

The number of nuclear reactors currently under construction is 63, giving a 70 GW plus boost in capacity which is one of the highest figures seen since 1990. At the same time, during the past five years, companies have chosen to keep operating over 60 reactors, almost 15% of the worldwide total. A project involving many governments is underway, aiming to greatly extend the use of nuclear energy by tripling it around the world by the year 2050 [3,4]. Moreover, this action reveals that nuclear energy can help sustain the shift to clean, sustainable energy generation. Besides, the expanding nuclear industry is clear from the fact that every year, investments in both reactor construction and reactor lifetime extensions have increased almost 50% since 2020 and surpassed USD 60 billion [5]. It shows more and more people around the world believe nuclear power can help meet their long-term energy needs sustainably.

As a result, AI integration makes NPPs safer, more efficient, better at predictive maintenance and resistant to cyber risks, attributes important in this industry. AI applications significantly contribute to making reactors more efficient, identifying faults faster and letting decisions be taken in real time to avoid system failures and replace unannounced shutdowns [6-8]. Using the power of machine learning and deep learning, AI can review tremendous amounts of sensor data to accurately predict when equipment will fail which leads to easier predictive upkeep and lower maintenance costs. AI assisted automation also prevents workers from making mistakes in major reactor tasks such as handling fuel, managing heat transfer and watching radiation levels.

In addition to running plants, AI improves the way nuclear energy fits with alternative sources because it helps balance grids, match loads and distribute power in mixed energy systems [9]. In addition, SMRs and new nuclear technologies can highly benefit from using AI for design improvements, licensing support and the setup of autonomous nuclear operations, leading to faster introduction of clean nuclear solutions [10]. AI is very important for nuclear power plants in working towards Net Zero Emissions by 2050, since it secures energy supplies, lowers overall costs and promotes a sustainable future for nuclear energy [11]. As AI improves, it will join nuclear power systems and improve how plants operate and are supervised, making nuclear energy an even more secure, trustworthy and smart electricity option for the years to come.

This literature review provides a comprehensive analysis of existing research on AI applications in nuclear power plants, examining recent advancements, technological developments, and implementation challenges. As matter of fact, the review explores key areas such as machine learning for predictive maintenance, deep learning for fault diagnosis, computer vision for automated inspections, and AI-driven decision support systems. Table 1 indicates recent studies on integrating of AI techniques with NPPs. The study presented in [12] aimed to systematically categorize, review, and analyze the barriers hindering the adoption of AI and Machine Learning (ML) within the nuclear power industry, with a particular emphasis on existing commercial reactors while also addressing unique considerations for advanced reactor technologies.

Sun et al. [18] conduct an in-depth investigation into the feasibility of integrating intelligent electrical equipment and smart maintenance technologies within nuclear power plants (NPPs) to enhance their existing automation and intelligence levels. The study emphasizes the critical role of AI-driven advancements in optimizing operational efficiency, improving maintenance strategies, and addressing the current limitations of traditional systems. The paper begins by identifying the demands and challenges associated with the implementation of intelligent electrical systems in NPPs, providing insights into their current development status. Liu et al. [19] explored the application of deep neural networks (DNNs) in nuclear power fault diagnosis, highlighting their growing prominence in conjunction with advancements in AI technologies. While these models offer substantial improvements in fault detection accuracy and predictive maintenance, their inherent "black box" nature raises significant concerns regarding interpretability and trust, particularly in safety-critical environments like NPPs. To address this challenge, the study introduces an explainable artificial intelligence (XAI) approach, leveraging game theory-based methodologies to conduct a detailed analysis of the diagnostic behavior of neural networks.

Table 1: A recent study on integration of AI techniques with NPPs.

Ref.	Year	Highlighted	Advanced Tanique's
[13]	2025	▪ The integration of Artificial Intelligence (AI) techniques and human intelligence is pivotal in the operation of Nuclear Power Plants (NPPs), particularly within advanced control room environments where human operators play an active role in decision-making. ▪ This study introduces a novel AI-driven fault diagnosis algorithm that leverages advanced Machine Learning (ML) and Deep Learning (DL) methodologies to improve decision-making processes in NPPs. ▪ The fault diagnosis algorithm is specifically designed to predict and classify normal and abnormal operational states in NPPs, focusing on high-risk accident scenarios like Turbine Trip with Anticipated Transient Without Scram (ATWS), Loss of Flow Accident (LOFA), and Loss of Coolant Accident (LOCA).	ML & DL
[14]	2025	▪ AI is revolutionizing nuclear energy and technology by providing advanced solutions to longstanding challenges through machine learning (ML) and deep learning (DL) techniques. ▪ The study highlights AI's significant role in radiation detection by leveraging pattern recognition and predictive analytics to enhance real-time monitoring and contamination assessment. ▪ This study underscores the importance of interdisciplinary collaboration between AI specialists, nuclear engineers, and policymakers to develop comprehensive safety guidelines and legal frameworks that address AI's integration in nuclear energy systems.	ML & DL
[15]	2025	▪ To address this limitation, pyMAISE (Michigan Artificial Intelligence Standard Environment) is introduced as a comprehensive Python package designed to automate hyperparameter tuning, model explainability, training, validation, postprocessing, and deployment for ML models in nuclear engineering. ▪ The pyMAISE framework supports ML model development across nine benchmark problems, spanning reactor physics and design, reactor control, thermal hydraulics, fuel performance, safety analysis, and anomaly detection. ▪ Experimental results validate pyMAISE's capability in identifying optimal AI/ML models, demonstrating superior performance compared to conventional approaches.	ML
[16]	2024	▪ The study highlights the inherent limitations of the BP neural network, particularly its tendency to converge to local optima, leading to reduced predictive accuracy and slower response times when forecasting transient nuclear parameters. ▪ To enhance the efficiency and accuracy of transient parameter prediction, this study introduces the Firefly Algorithm (FA) to optimize the BP neural network.	FA–BP
[17]	2023	▪ The study investigates collection and evaluation of data with ML models and statistics to diagnose faults in systems. The use of Artificial Neural Networks (ANN), Support Vector Machines (SVM), Principal Component Analysis (PCA), Decision Trees (DT) and clustering algorithms is studied, together with approaches that join multiple algorithms.	ML ANN SVM PCA DT

The article states that the increasing use of ML and AI in the nuclear sector is creating many projects by Spanish businesses and institutions aimed at improving how nuclear energy is operated. The research reviews the different types of these initiatives, covering areas such as analyzing nuclear data, producing nuclear fuel, simulation, fuel monitoring, checking nuclear systems and training operators. In these projects, deep neural networks are used for surrogate modeling, CNNs for computer vision functions, Bayesian networks and Gaussian processes for predicting outcomes and large language models are applied for speech recognition in nuclear operations.

This work analyzes AI in NPPs and explains its role in maintaining safety, boosting operations, conducting preventive maintenance and managing cyber risks. This article explores the theory underlying AI in nuclear systems, look at their history and analyze how ML and DL are used for spotting faults, spotting anomalies and making decisions. It also explores AI-enabled mobile computing and how it connects with nuclear-related technologies, private cloud structures, IoT and Blockchain. Key issues found in the study include following regulations, working with AI alongside people, security issues, tying costs, training workers and issues with how data is used in AI.

Defining Artificial Intelligence (AI)

Because AI covers multiple fields, it is difficult to define since it has many concepts, calculations and philosophical aspects. In their framework, Russell and Norvig point out that AI is not purely conventional programming and also covers cognitive, rational and adaptive thinking [18-21]. As part of the larger field, Turing's suggestion provided the first benchmark for determining how effectively an AI could behave the same way a person would in interaction with the system. For AI to imitate human thinking, it relies on fields such as neuroscience and psychology. Such models help us understand how humans think, but they struggle to deal with the detailed cultural, emotional and contextual factors that influence reasoning [22].

An intriguing method in AI is the building of systems that use formal rules as a framework for logical reasoning to resolve problems. Despite its adherence to a rigid rule-based framework, logic-based AI struggles to effectively address real-world issues that may be ambiguous or intricate. To tackle these issues, contemporary AI algorithms often include probabilistic reasoning alongside their logical frameworks, enabling them to handle situations that inflexible rules cannot manage. Consequently, AI is seen as facilitating the development of agents that comprehend necessary tasks, recognize possible actions, and choose the optimal course for achieving their objectives. The implementation of flexible options and prompt reactions in real time guarantees that the agent-based model is scalable and operates well, making it a fundamental method for using AI across many applications [22].

AI classification is mostly based on scope and abilities and these fit into three groups: Narrow, General and Super intelligent. At present, narrow AI is used for many AI applications, focusing on image recognition, processing language and controlling devices on its own [23]. In contrast, developing Artificial General Intelligence (AGI) is just a theory, dedicated to computers being able to think adaptively just like people in many different areas [24,25]. The theory of a possible "Singularity" demonstrates both the important new possibilities and major unanswered questions that characterize modern AI discussions in important areas such as nuclear energy and autonomous systems [26,27].

The Importance of AI in Nuclear Power Plants

AI in NPPs is transforming the field by improving how things are run, kept safe, maintained and protected from internet attacks. Since nuclear power continues to play a big role in cutting emissions, AI technology is needed to enhance reactor performance, keep downtime low and ensure reactor operators comply with regulations. With more advanced nuclear systems, AI helps monitor and interpret information, automated and intelligent operations, all which cut down on mistakes and improve the plant's performance [27-30].

- **Predictive Maintenance and Fault**

Diagnosis is a subfield of machine learning. Tools using AI's predictive maintenance analyze information from real-time sensors, detect gradual changes in equipment and prevent surprising problems. As a result, there is less downtime without notice, lower costs for maintenance and the plant runs more reliably.

- **Improving the Safety and Risk Control of Nuclear**

Reactors Such systems are designed to check the operation of the reactor, its radiation status and structure continually, so risks can be found early. Automated fault detection by Deep learning is used to make sure equipment stays up to strict safety standards.

- **Achieving Better Efficiency in Regular Work and Main Operations**

With AI, process control is now automatic which improves the way reactor fuel, cooling and energy are handled. AI examines operational information to control how much power is generated, how resources are tracked and how best to deliver energy which helps save money and improve performance.

- **The domain encompasses cybersecurity and threat detection**

As an increasing number of nuclear power facilities transition to digital operations, artificial intelligence is essential in mitigating and addressing cyber risks. AI-driven solutions for intrusion detection and user behavior analysis complicate the efforts of attackers to compromise nuclear plants.

- **Utilizing machines for inspection and quality assessments**

AI assists robotics and visual systems in doing non-destructive testing, structural assessments, and monitoring radiation exposure, hence reducing dangers for people in hazardous areas. Artificial intelligence facilitates the identification of product flaws, hence enhancing overall safety and quality assurance.

AI Application in NPPs

The introduction of AI is vital now as the nuclear sector adopts modern reactors and digital infrastructure that help ensure plants function safely. The investigation of AI technology in education and the history of digital growth in nuclear power plants are the main focuses of this article, helping us see clearly how AI transformed nuclear energy [31-33]. The fundamental concept of AI is its ability to use software and computation to replicate cognitive information processing. Machine Learning (ML) is a specific area in AI that gives systems or processes the ability to process knowledge found in data and carry out detailed jobs such as making predictions and classifying things. There are three categories for AI which are called supervised, semi-supervised and unsupervised learning. The process of supervised learning depends on labeling training data well which helps the model handle new examples. In contrast, unsupervised learning focuses on uncovering hidden structures within unlabeled data.

For safety reasons, high-stakes industries such as nuclear power have benefited from machine learning methods, among them linear regression, support vector machines, random forests and artificial neural networks. But the process of finding the most important features in ML models is often costly which can seriously limit its use. To solve this problem, deep learning (DL) has evolved in ML, making use of top computational systems and algorithms to speed up model learning. One of the main reasons for DL's success is that architectures like DNNs, CNNs and RNNs are used for analyzing large amounts of data. Apart from ML and DL, significant progress in nuclear energy has occurred with Evolutionary Algorithms (EA). Various AI algorithms are shown in Figure 1 as used in research related to nuclear power plants. Using genetic algorithms, ant colony optimization and particle swarm optimization, optimization techniques help deal with the tough, nonlinear challenges seen in nuclear reactor design.

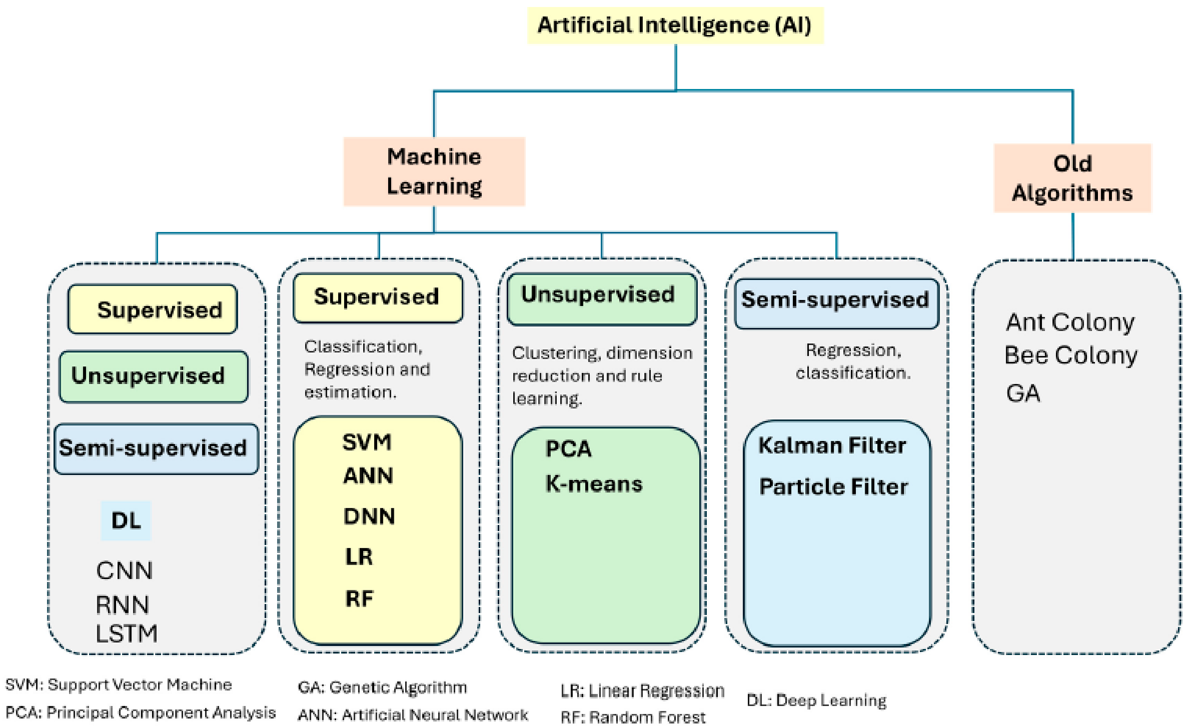

Figure 1. Outline of the latest AI algorithms employed by NPPs [34].

Both AI-driven techniques and the continually expanding database of nuclear power plants are contributing strongly to the development of nuclear system analysis, simulation and optimization. AI tools are bringing great changes to how the nuclear industry acquires knowledge and runs its activities. New advances in AI now make it possible to improve the accuracy and effectiveness of systems based on knowledge in nuclear plants. Advanced AI and ML algorithms are expected to play a major role in enhancing the safety, reliability and assessing risks within nuclear plants thanks to studies carried out by the Idaho National Laboratory for the Nuclear Regulatory Commission. Through using these tools, nuclear energy developers and operators address system design, plant operation, maintenance and incident resolution, helping build a safer and smarter infrastructure for the future.

Historical Evolution of Digital Technologies in Nuclear Power Plants

Over the years, nuclear power plants (NPPs) have shifted, step by step, from using analog I&C systems to using complex digital ones. Technological progress, the expiry of early systems and a goal to upgrade safety and reliability have mostly been responsible for driving this change [35]. After moving from analog to digital systems, nuclear power operations have experienced greater automation, best-in-class monitoring and improved ability to catch faults, diagnose them early and maintain equipment with more accuracy. On top of that, the rise of mobile computing has been central to revolutionizing nuclear energy systems by including smart devices in many subsystems and interfaces. Ever since the 1980s, using smart technologies in NPPs has been understood as a key step towards dealing with rising safety issues, following rules and coping with the more complex aspects of running nuclear plants. The many smart devices available now provide improved data collection, better system compatibility and improved use of resources, so they are essential for current nuclear facilities [35].

An important case of this combination is the use of wireless sensor networks (WSNs) which have transformed real-time monitoring and control inside NPPs. Thanks to these networks, collecting, processing and sharing important plant data for predictive purposes, early warnings and reducing risks is much simpler. Using WSNs in nuclear power systems is part of a wider movement to add intelligence technology into fields such as the military, environmental services and automating factories [36]. Because of this development, organizations are using smart and interconnected systems more widely to support quicker and better decision-making, better results and stronger ability to cope in difficult environments.

Mobile Computing in Nuclear Power Stations

In this part, the paper talks about the structure of AI-supported mobile computing, the support private cloud gives to AI-driven mobile tech in nuclear plants and what impact IoT, AI and Blockchain might have in both the industrial and nuclear sectors [37-40].

- **Framework of AI-Driven Mobile Computing**

When AI is added to modern mobile devices which are easy to use and are part of advanced 5G technologies, businesses gain several key benefits in terms of data analysis, automation and network protection. AI-powered mobile computing uses three important parts: perception, cognition and decision-making. When joined, these components make mobile networks flexible and able to automatically adjust in response to both shifting operations and user preferences. On top of everything, the perception layer collects data by gathering details from all sorts of sources, among them MTD, RAND and PCND. This integration of multiple data streams in this layer supports accurate awareness of the situation and ensures precise results in following AI-based analyses [37,38]. Thanks to the cognition layer, the AI architecture utilizes AI and ML processes to examine and learn from the huge volumes of data gathered by the perception layer. With this, it can observe how users behave, where they visit, how the network is used and how services are performing over time. Deep learning, reinforcement learning and predictive analytics are used in the cognition layer to increase the network's flexibility, better allocate resources and boost overall service performance.

Data acquisition leads on to a cognition phase where advanced ML and DL algorithms are used to process huge amounts of sensor data. The analysis allows the system to spot trends, find unusual situations and notice hints of failures that could turn into dangerous accidents. The cognition layer alerts plant managers at the first signs of unsafe conditions using pattern recognition, anomaly detection and predictions. Following the information collected during cognition, the part in charge of making decisions picks the correct response. Based on how significant and what type of anomaly is discovered, the system may [38-41]:

- Raise instant alerts for plant operators whenever dangers might develop.
- Set up a schedule for preventive care, so that early clues of failure do not worsen into big issues.
- Safety and stability benefit from those systems that can modify the cooling system or regulate the reactor on their own.

The proposed architecture for AI-backed mobile computing creates a tight link among perception, cognition and decision-making, allowing both mobile operators and industry sectors to apply AI and big data for better system planning, optimization, operation and management. With this framework, computing systems are able to adapt instantly, anticipate events and manage themselves well which greatly increases the reliability of large infrastructures. With AI-driven mobile computing, the nuclear power industry can expect a big technical advance, thanks to its better performance, dependability and increased safety. Because mobile devices with AI can continue learning, change with dynamic circumstances and take actions without human direction, they help businesses accomplish intelligent automation, predictive maintenance and take action ahead of risks.

- **Private Cloud Infrastructure for AI-Driven Mobile Computing in Nuclear Power Plants**

Public cloud solutions are not the ideal choice in using AI-integrated mobile computing and nuclear plant applications, so many prefer the more strategic private cloud option. One key advantage is the improved control, management and security a private cloud delivers which is very important in the strictly controlled and data-handling world of nuclear facilities [41]. Because the NPP operator holds all of the authority in a private cloud environment, there is strong central control over things like security, data privacy, how the network is managed, compliance, auditing and governance. For important nuclear uses, it is absolutely essential to control access, as tough regulations and excellent cybersecurity are required. Since a private cloud is not shared, it is safer than public clouds because it reduces risks from data breaches, access by unauthorized users and difficulties with interrupted services.

The management system in a private cloud must provide full control over services to ensure these applications perform reliably, remain widely available and achieve the best performance in the nuclear power plant (NPP). Features for tracking SLA, applying patches, producing reports and handling incidents form part of this. The private cloud needs to strictly manage the Service-Level Agreement (SLA), making sure that computers, data accessibility and the platform's availability always meet the key needs of running the nuclear plant. That's why AI works so well in these systems, helping to minimize downtime and avoid interruptions in the safety, maintenance and intelligence areas.

- Patch management is important because it should update security, firmware and software in the private cloud in a central and automated manner. This reduces risks, improves cybersecurity and helps companies obey industry laws, so unauthorized access or cyber dangers are avoided.
- Reporting and Analytics: Monitoring and collection of performance level, tasks sharing and data safety should be enabled with real-time tools. Based on these insights, companies can make decisions early, use resources wisely and recognize performance problems that may trouble AI and mobile computing before they become serious.

Included is the need for incident software capable of detecting, diagnosing and addressing issues without human intervention. Such models can notice system failures in advance, organize immediate alerts and apply automated solutions to keep NPP operations uninterrupted. Utilizing these functions, the private cloud structure evolves into a robust, self-optimizing environment that facilitates high-performance AI-driven mobile computing while maintaining rigorous adherence to regulatory and security norms. This methodology enhances data quality, operational efficiency, and system stability, making it an essential foundation for the digital transformation of contemporary nuclear power plants [41]. Figure 2 shows a standard private cloud infrastructure engineered to provide exceptional operational control, and customized functionalities, guaranteeing the enhance of AI-driven mobile computing applications.

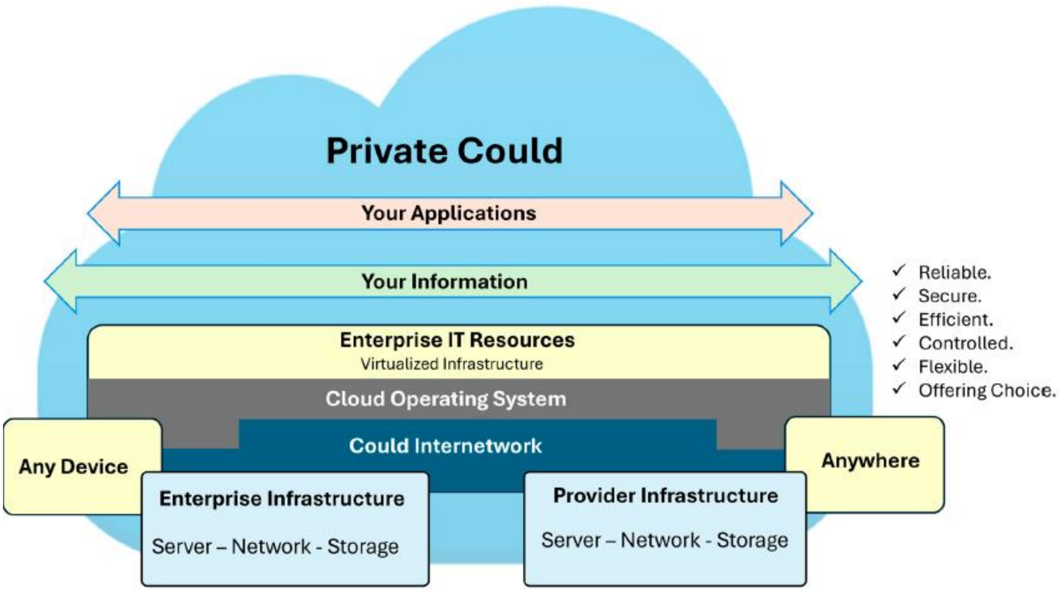

Figure 2. A typical private cloud infrastructure [36].

The combination of blockchain, artificial intelligence (AI), and Internet of Things (IoT) technology is anticipated to drastically alter business and industrial processes in the near future, including highly regulated industries like nuclear power generation. Significant improvements in efficiency, security, and decision-making capabilities will result from this convergence, which will make it easier to collect data in real-time, automate tasks intelligently, and manage data securely in a decentralized manner [42]. Even though IoT devices are the main layer for gathering data, their full potential only becomes apparent when the data is examined, deciphered, and used to make well-informed decisions, a process that is made possible by the integration of AI. Large-scale IoT-generated datasets can be processed by AI algorithms, which can then spot trends, anticipate abnormalities, and instantly improve system performance.

This is especially important in nuclear power plants (NPPs), where operational safety and efficiency are ensured by predictive maintenance, risk assessment, and ongoing monitoring. There are numerous important benefits to using AI and IoT together in nuclear power plant operations [42–45]. IoT-enabled sensors continuously collect data on pressure, temperature, radiation levels, and other vital plant parameters. AI can then analyze and spot patterns that might point to early warning signs of breakdowns or inefficiencies.AI-powered predictive analytics and automated diagnostics facilitate real-time decision-making, assisting operators in anticipating possible hazards and maximizing reactor performance. AI-powered IoT systems can help with rapid situation assessment, emergency protocol initiation, and autonomous process adjustment to reduce risks and avert catastrophic failures throughout critical mistake scenarios.

Using blockchain technology for data security and integrity strengthens cybersecurity and regulatory compliance in nuclear infrastructure by providing tamper-proof, unchangeable records of operational data. Safety, efficiency, and decision intelligence will be improved in nuclear power plants and other industrial sectors as a result of the synergistic integration of IoT, AI, and blockchain. A safer and more flexible energy subsequent years will be made possible by these technologies, which will make possible the transition to smart, self-optimizing nuclear facilities.

Nevertheless, in order to deploy and use the Internet of Things (IoT) in nuclear power plants (NPPs) effectively, a strong and specialized infrastructure must be established. NPPs require a complex IoT infrastructure that includes a wide range of networked devices, sophisticated sensor networks, and robust connectivity systems to enable smooth data collection and transfer as shown in Figure 3. Furthermore, the IoT infrastructure needs to have strict cybersecurity measures, such as a highly secure data transmission network and a fortified data storage interface, because nuclear facilities are critical. In order to reduce possible cybersecurity risks and protect the safety and integrity of the data that is sent and stored within the Internet of Things ecosystem, these steps are essential.

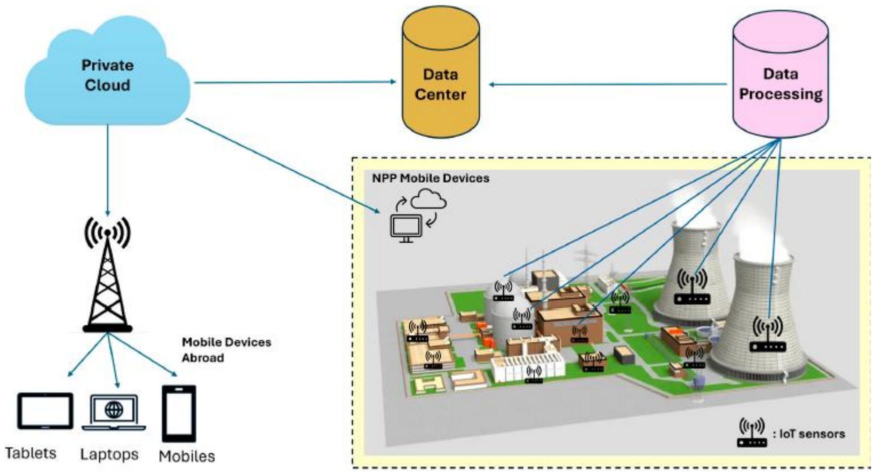

Figure 3. Diagram of IoT infrastructure throughout nuclear power stations [36].

Challenges

The use of Machine Learning (ML) and Deep Learning (DL) approaches has greatly advanced the integration of AI technologies in nuclear reactor research. By precisely predicting nuclear power states and dynamically optimizing operational scheduling, including maintenance intervals, these advanced algorithms improve predictive capabilities and help nuclear facilities reduce costs and mitigate risk. Notwithstanding these developments, scalability and applicability issues make it extremely difficult to apply AI-driven approaches in the nuclear energy industry. The main obstacles that must be removed in order to enable real-world deployment and integration of AI and mobile computing technologies into nuclear power plant activities are well-explained in Figure 4.

- **Data Issues**

The accessibility and reliability of sources of information and patterns present one of the main obstacles to the integration of AI in nuclear power plants (NPPs). Furthermore, a major problem is that simulation-based datasets are typically used instead of actual data collected directly from nuclear power plants. Large-scale real-time data collection is impractical due to the risky, expensive, and resource-intensive nature of conducting thorough, real-world experimental studies within NPPs. Because of this, most of the research in this field relies on simulated data records, which introduce inherent differences between simulated and real-world data even though they are helpful for training and validating models.

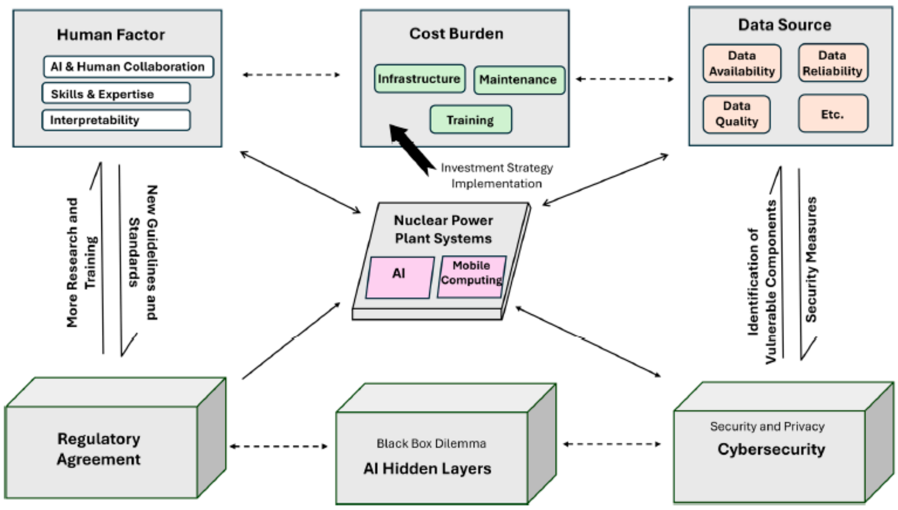

Figure 4. Barriers to applying of AI and mobile computing in NPPs [36].

- **Black Box Dilemma: AI Invisible Hidden Layers**

The "black box" dilemma, which arises from the transparent and non-transparent nature of deep learning (DL) designs, is a significant obstacle in the application of AI in nuclear power plant research, as discussed in this subsection. The inbuilt decision-making processes within DL architectures are also challenging to understand due to their hidden layers and complex feature encoding procedures, raising serious questions about regulatory compliance, trust, and accountability in nuclear safety-critical environments. Although high-performance models provide better predictive accuracy, they frequently sacrifice explainability, making it difficult for human operators to completely comprehend or verify their results.

- **Cybersecurity Within Mobile Computing**

Because sensitive reactor data is virtually transmitted across mobile devices, integrating AI and mobile computing in nuclear power plants (NPPs) poses significant cybersecurity challenges. NPPs' digital instrumentation and control (I&C) systems are vulnerable to a variety of cyberthreats, so in order to protect both wired and wireless networks, a thorough grasp of attackers' skills, intentions, and techniques is required. Cyber adversaries, which include nation-state actors, disgruntled insiders, and cyber-activists, have different levels of expertise, resources, and intent. They use sophisticated attack techniques like denial-of-service (DoS) attacks, packet sniffing and modification, system spoofing, mimicking, and man-in-the-middle (MITM) attacks to exploit system vulnerabilities [45]. The safe implementation and operation of AI-driven mobile information technology solutions in NPPs is severely hampered by the complexity of these sophisticated persistent hazards (APTs), especially those that come from nation-state actors.

- **Regulatory Compliance Challenges**

Nuclear power plants (NPPs) must integrate mobile computing and artificial intelligence (AI) in order to handle the special risks and operational complexity brought about by these technologies. This calls for a review and modification of current regulatory frameworks as well as the creation of new guidelines. In order to maintain the highest safety and reliability standards while guaranteeing regulatory compliance, industry stakeholders, regulatory agencies, and AI specialists must work together to create explicit governance policies and risk-reduction plans [45].

- **AI and Human Collaboration Challenges**

A paradigm shift in human roles is represented by the integration of AI and mobile computing in NPPs, which move operators from manual control tasks to supervisory and decision-support roles. For plant operations to be safe, effective, and optimal, human operators and AI systems must work together seamlessly. To promote successful human-machine synergy, thorough training programs and ergonomic system designs are necessary due to issues with trust-building, cognitive workload distribution, and human-AI interaction protocols [46].

- **Cost Challenges**

The deployment of AI and mobile computing technologies in nuclear power facilities entails substantial financial investments, encompassing infrastructure development, workforce training, and continuous maintenance costs. Balancing the long-term benefits of AI integration, like as enhanced safety, efficiency, and automation, against the significant upfront and operational expenses poses a challenge for NPP stakeholders. Strategic cost-benefit analyses, phased implementation approaches, and funding mechanisms are essential to justify expenditures and maximize returns [47].

- **Training and Expertise Challenges**

A highly qualified workforce that can use and manage AI-driven technologies is essential to the nuclear industry's successful adoption of mobile computing and AI. This calls for the recruitment of AI experts from other fields as well as the establishment of specialized training courses for current nuclear staff. To close the knowledge gap and enable seamless technological integration in NPPs, it is also advised to cultivate interdisciplinary expertise by combining AI experts with nuclear energy specialists [48].

Conclusion

An important step toward guaranteeing operational effectiveness, predictive maintenance, and improved safety measures is the incorporation of artificial intelligence (AI) into nuclear power plants (NPPs). AI-powered solutions are revolutionizing process optimization, risk assessment, and fault detection, reducing human error and increasing automation in nuclear operations. The basic definitions of artificial intelligence (AI), its significance in the nuclear industry, and its uses in learning-based technologies and digital transformation in nuclear power plants have all been covered in this article. The development of digital technologies in nuclear plants over time has also paved the way for machine learning (ML) and deep learning (DL) applications, which facilitate data-driven decision-making and anomaly detection systems that enhance plant dependability and resilience.

AI-driven mobile computing is one of the most exciting advancements in this area since it allows for intelligent decision support, remote control, and real-time monitoring in nuclear environments. The framework of AI-integrated mobile computing has also been reviewed in this review, with a focus on the function of private cloud infrastructures in protecting AI-driven operations and reducing cybersecurity threats. Additionally, it is anticipated that the future convergence of blockchain, artificial intelligence, and the Internet of Things (IoT) will transform the nuclear and industrial energy sectors by enabling decentralized, transparent, and extremely secure operational ecosystems. With the potential for improved automation, predictive analytics, and energy management, these developments establish AI as a key component of next-generation nuclear power systems.

The application of AI in nuclear power plants is hampered by technical, legal, and financial issues, despite its enormous potential. To ensure that safety and operational procedures keep up with changing technological landscapes, regulatory compliance frameworks must adapt to AI-driven automation and decision-making. Similarly, the black box problem is still a major worry since deep learning models' opaqueness restricts their interpretability and reliability in high-stakes nuclear settings. Adoption of AI is further hampered by data availability issues brought on by the use of simulated datasets rather than actual data. In order to protect sensitive nuclear infrastructure, cybersecurity threats, especially in AI-integrated mobile computing environments, present serious risks that call for sophisticated threat detection, intrusion prevention systems, and strong encryption models. Careful thought must also be given to the financial effects of AI adoption in NPPs. The long-term advantages of AI-driven automation must be balanced against the high expenses of infrastructure investment, employee training, and continuing maintenance. Together with that, cooperation between AI experts, nuclear engineers, legislators, and cybersecurity specialists is essential to guaranteeing the successful deployment of AI and promoting a multidisciplinary approach to AI governance in nuclear power applications. The workforce must also adjust significantly to the shift from manual to AI-assisted supervisory control, which emphasizes the necessity of specialized training programs to get staff members the technical know-how they need. In conclusion, even though artificial intelligence (AI) has enormous potential to improve safety, streamline operations, and guarantee the long-term viability of nuclear power plants, its integration needs to be planned for, carefully regulated, and security-conscious. Addressing the current constraints and guaranteeing responsible AI deployment in nuclear facilities depends on future developments in explainable AI (XAI), hybrid AI models, and human-AI collaborative frameworks.

Reference

[1] M. Khaleel *et al.*, “Harnessing nuclear power for sustainable electricity generation and achieving zero emissions,” *Energy Explor. Exploit.*, 2025.

[2] J. Kim, S. Lee, and P. H. Seong, *Autonomous nuclear power plants with artificial intelligence*. Cham: Springer International Publishing, 2023.

[3] R. Jayabal, “Next-generation solutions for water sustainability in nuclear power plants: Innovations and challenges,” *Nucl. Eng. Des.*, vol. 432, no. 113757, p. 113757, 2025.

[4] B.-G. Jeon, D.-U. Park, S.-W. Kim, S.-J. Chang, S. Eem, and J. Park, “A case study on the failure of the electrical panel of nuclear power plants by shaking table tests,” *Nucl. Eng. Technol.*, no. 103533, p. 103533, 2025.

[5] M. Khaleel, Z. Yusupov, and S. Rekik, “Exploring trends and predictions in renewable energy generation,” Energy 360, no. 100030, p. 100030, 2025.

[6] S. A. Cancemi, M. Angelucci, A. Chierici, S. Paci, and R. Lo Frano, “Hybrid neural network and statistical forecasting methodology for predictive monitoring and residual useful life estimation in nuclear power plant components,” Nucl. Eng. Des., vol. 433, no. 113900, p. 113900, 2025.

[7] T. Zhang, T. Wan, W. Pan, and S. Liu, “Prospects of nuclear power plant operation and maintenance technology in the era of artificial intelligence,” in *2022 the 3rd International Conference on Service Robotics Technologies*, 2022.

[8] G. Zhou and D. Tan, “Review of nuclear power plant control research: Neural network-based methods,” *Ann. Nucl. Energy*, vol. 181, no. 109513, p. 109513, 2023.

[9] D. G. Lanin, “Topical issues of the introduction of artificial intelligence into the design process of nuclear power plants,” *Power Technol. Eng.*, vol. 56, no. 6, pp. 929–936, 2023.

[10] B. Qi, X. Xiao, J. Liang, L.-C. C. Po, L. Zhang, and J. Tong, “An open time-series simulated dataset covering various accidents for nuclear power plants,” *Sci. Data*, vol. 9, no. 1, p. 766, 2022.

[11] M. Khaleel *et al.*, “Evolution of emissions: The role of clean energy in sustainable development,” *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[12] A. Hall and V. Agarwal, “Barriers to adopting artificial intelligence and machine learning technologies in nuclear power,” *Prog. Nuclear Energy*, vol. 175, no. 105295, p. 105295, 2024.

[13] A. A. Elbordany, M. M. Kandil, H. A. Youness, and H. M. Abdelaal, “An efficient AI algorithm for fault diagnosis in nuclear power plants based on machine deep learning techniques,” *Prog. Nuclear Energy*, vol. 180, no. 105580, p. 105580, 2025.

[14] A. A. Elbordany, M. M. Kandil, H. A. Youness, and H. M. Abdelaal, “An efficient AI algorithm for fault diagnosis in nuclear power plants based on machine deep learning techniques,” *Prog. Nuclear Energy*, vol. 180, no. 105580, p. 105580, 2025.

[15] P. A. Myers *et al.*, “pyMAISE: A Python platform for automatic machine learning and accelerated development for nuclear power applications,” *Prog. Nuclear Energy*, vol. 180, no. 105568, p. 105568, 2025.

[16] Z. Liu, T. Liu, and G. Peng, “Optimization of BP neural network for fault parameter prediction in nuclear power plants utilizing the firefly algorithm,” J. Nucl. Sci. Technol., vol. 62, no. 1, pp. 86–97, 2025.

[17] B. Qi, J. Liang, and J. Tong, “Fault diagnosis techniques for nuclear power plants: A review from the artificial intelligence perspective,” Energies, vol. 16, no. 4, p. 1850, 2023.

[18] Y. Sun, Z. Wang, Y. Huang, J. Zhao, B. Wang, X. Dong, and C. Wang, “The evolving technological framework and emerging trends in electrical intelligence within nuclear power facilities,” Processes, vol. 12, no. 7, p. 1374, 2024.

[19]

[20] J. Liu, Q. Zhang, and R. Macián-Juan, “Enhancing interpretability in neural networks for nuclear power plant fault diagnosis: A comprehensive analysis and improvement approach,” Prog. Nucl. Energy, vol. 174, p. 105287, 2024.

[21] A. Ramos, A. Carrasco, J. Fontanet, L. E. Herranz, D. Ramos, M. Díaz, J. M. Zazo, O. Cabellos, and J. Moraleda, “Artificial intelligence and machine learning applications in the Spanish nuclear field,” Nuclear Engineering and Design, vol. 417, p. 112842, 2024.

[22] G. Kyriakarakos, “Artificial intelligence and the energy transition,” Sustainability, vol. 17, no. 3, p. 1140, 2025.

[23] S. Russell and P. Norvig, Artificial Intelligence: A Modern Approach. Hoboken, NJ, USA: Prentice Hall, 2009.

[24] M. V. S. Babu and K. Banana, “A study on narrow artificial intelligence—An overview,” Int. J. Eng. Sci. Adv. Technol., vol. 24, pp. 210–219, 2024.

[25] S. Bubeck, V. Chandrasekaran, R. Eldan, J. Gehrke, E. Horvitz, E. Kamar, P. Lee, Y. T. Lee, Y. Li, and S. Lundberg, “Sparks of artificial general intelligence: Early experiments with GPT-4,” arXiv, 2023, arXiv:2303.12712.

[26] S. McLean, G. J. Read, J. Thompson, C. Baber, N. A. Stanton, and P. M. Salmon, “The risks associated with artificial general intelligence: A systematic review,” J. Exp. Theor. Artif. Intell., vol. 35, pp. 649–663, 2021.
[27] D. J. Chalmers, “The singularity: A philosophical analysis,” in Science Fiction and Philosophy: From Time Travel to Superintelligence, Hoboken, NJ, USA: Wiley, 2016, pp. 171–224.
[28] M. Sethu et al., “Application of artificial intelligence in detection and mitigation of human factor errors in nuclear power plants: A review,” Nucl. Technol., pp. 1–19, 2022.
[29] B. Qi, J. Liang, and J. Tong, “Fault diagnosis techniques for nuclear power plants: A review from the artificial intelligence perspective,” Energies, vol. 16, no. 4, p. 1850, 2023.
[30] M. M. Khaleel, A. A. Ahmed, and A. Alsharif, “Artificial Intelligence in Engineering,” Brilliance: Research of Artificial Intelligence, vol. 3, no. 1, pp. 32–42, 2023.
[31] Q. Huang et al., “A review of the application of artificial intelligence to nuclear reactors: Where we are and what’s next,” Heliyon, vol. 9, no. 3, p. e13883, 2023.
[32] G. Zhou and D. Tan, “Review of nuclear power plant control research: Neural network-based methods,” Ann. Nucl. Energy, vol. 181, no. 109513, p. 109513, 2023.
[33] J. H. Park, H. S. Jo, S. H. Lee, S. W. Oh, and M. G. Na, “A reliable intelligent diagnostic assistant for nuclear power plants using explainable artificial intelligence of GRU-AE, LightGBM and SHAP,” Nucl. Eng. Technol., vol. 54, no. 4, pp. 1271–1287, 2022.
[34] B. Hanna, T. C. Son, and N. Dinh, “AI-guided reasoning-based operator support system for the nuclear power plant management,” Ann. Nucl. Energy, vol. 154, no. 108079, p. 108079, 2021.
[35] I. Imbayah, A. Alsharif, M. Khaleel, A. A. Ahmed, and H. J. El-Khozondare, “Studying the Possibility of Smart Farms based on solar System Using (IoT) Technology in Libya,” *SUCP*, vol. 3, no. 2, pp. 97–102, 2024.
[36] IAEA (International Atomic Energy Agency). Safe Use of Smart Devices in Systems Important to Safety in Nuclear Power Plants; International Atomic Energy Agency: Vienna, Austria, 2023.
[37] Lin, R.; Wang, Z.; Sun, Y. Wireless sensor networks solutions for real time monitoring of nuclear power plant. In Proceedings of the Fifth World Congress on Intelligent Control and Automation, Hangzhou, China, 15–19 June 2004.
[38] L. Marques, A. Vale, and P. Vaz, “State-of-the-art mobile radiation detection systems for different scenarios,” Sensors (Basel), vol. 21, no. 4, p. 1051, 2021.
[39] O. Popov, A. Iatsyshyn, D. Sokolov, M. Dement, I. Neklonskyi, and A. Yelizarov, “Application of virtual and augmented reality at nuclear power plants,” in Studies in Systems, Decision and Control, Cham: Springer International Publishing, 2021, pp. 243–260.
[40] Z. Chen, H. Wu, Y. Chen, L. Cheng, and B. Zhang, “Patrol robot path planning in nuclear power plant using an interval multi-objective particle swarm optimization algorithm,” Appl. Soft Comput., vol. 116, no. 108192, p. 108192, 2022.
[41] S. Bharany et al., “A systematic survey on energy-efficient techniques in sustainable cloud computing,” Sustainability, vol. 14, no. 10, p. 6256, 2022.
[42] Kulkarni, G.A.; Patil, N.; Patil, P. Private Cloud Secure Computing. Int. J. Soft Comput. Eng. 2012, 2, 2231–2307
[43] M. Khaleel, A. Jebrel, and Dunia M. Shwehdy, “Artificial Intelligence in Computer Science”, *Int. J. Electr. Eng. and Sustain.*, vol. 2, no. 2, pp. 01–21, Mar. 2024.
[44] O. Popov, A. Iatsyshyn, D. Sokolov, M. Dement, I. Neklonskyi, and A. Yelizarov, “Application of virtual and augmented reality at nuclear power plants,” in Studies in Systems, Decision and Control, Cham: Springer International Publishing, 2021, pp. 243–260.
[45] H. M. Rai, K. K. Shukla, L. Tightiz, and S. Padmanaban, “Enhancing data security and privacy in energy applications: Integrating IoT and blockchain technologies,” Heliyon, vol. 10, no. 19, p. e38917, 2024.
[46] A. Ayodeji, M. Mohamed, L. Li, A. Di Buono, I. Pierce, and H. Ahmed, “Cyber security in the nuclear industry: A closer look at digital control systems, networks and human factors,” Prog. Nuclear Energy, vol. 161, no. 104738, p. 104738, 2023.
[47] D. A. Ejigu, Y. Tuo, and X. Liu, “Application of artificial intelligence technologies and big data computing for nuclear power plants control: a review,” Front. Nucl. Eng., vol. 3, 2024.
[48] Y. Chen, R. Zhang, J. Lyu, and Y. Hou, “AI and Nuclear: A perfect intersection of danger and potential?,” Energy Econ., vol. 133, no. 107506, p. 107506, 2024.