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Review

A Survey of Artificial Intelligence Applications in Nuclear Power Plants

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Abstract: Nuclear power plants (NPPs) rely on critical, complex systems that require continuous monitoring to ensure safe operation under both normal and abnormal conditions. Despite the potential of artificial intelligence (AI) to enhance predictive capabilities in these systems, limited research has been conducted on the application of AI algorithms within NPPs. This presents a knowledge gap in the integration of AI for improving safety, reliability, and decision making in NPP. In this study, we explore the use of AI methods, including machine learning and real-time data analytics, applied to NPP components to address the nonlinearity and dynamic behavior inherent in reactor operations. Through the implementation of AI and Internet of Things (IoT) devices, we propose a system that enables early warning and real-time data transmission to regulatory authorities and decision-makers, ensuring better coordination during incidents. Lessons from past nuclear accidents, such as Chernobyl, emphasize the importance of timely information dissemination to mitigate risks. However, this integration also presents challenges, including cybersecurity risks and the need for updated regulations to address AI use in safety-critical environments. The results of this study highlight the urgent need for further research on the application of AI in NPPs, with a particular focus on addressing these challenges to ensure safe implementation.

Keywords: artificial intelligence (AI); machine learning (ML); mobile computing; nuclear power plant (NPP); Internet of Things (IoT); cloud computing; prediction algorithms; cybersecurity; data collection; safety and reliability

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1. Introduction

Nuclear power plants (NPPs) are highly complex, interconnected systems of large numbers of critical subsystems and components. While the malfunction of non-safety systems typically does not affect overall plant safety, the failure of safety-critical systems could propagate through the plant if not adequately contained. However, it is important to note that all large commercial nuclear power plants are designed according to the single-failure criterion, ensuring that a single component failure will not compromise the functionality of safety-critical systems, thus preventing accidents. Safety and optimal performance during operational life have paramount importance and demand a full understanding of the nonlinear dynamic behavior of the plant. The lessons learned from the Fukushima Daiichi accident underscored the importance of robust and resilient monitoring systems for safe operation and accident management. However, it should be noted that the failure of monitoring systems during Fukushima was primarily due to a total plant power outage, a situation in which even AI or soft computing technologies would not have been able to function. Nevertheless, in scenarios where power is maintained, AI-driven monitoring systems can significantly enhance operational safety and decision-making capabilities [1]. Real-time coordination and early warning systems are therefore essential because they offer much more than monitoring functions; instead, they also offer effective predictability of nonlinear dynamic behavior of nuclear power systems components, subsystems, and the full system under normal and transient operating conditions [1]. The fast transmission of early warning information through mobile networking can drive effective risk mitigation strategies, taking complex considerations into high consideration to act as a very valuable decision support system for plant operators. Decision making within the dynamic and highly interdependent environment of NPPs can be challenging, necessitating the adoption of intelligent and adaptive, plant-specific predictive systems to ensure the safety of the plant, environment, and the public [1]. Predictive intelligent systems are designed for collecting overflow data, organizing them, and analyzing them with the target of making informed decisions during emergency situations. Such data, however, may have difficult meanings to extract, and more sophisticated tools are required to predict a system's response under various operating conditions [1]. Artificial intelligence provides us with faster and more efficient tools that can learn by themselves from the patterns in the data, hence having the potential to predict the behavior of complex systems through intelligent algorithms. Mobile computing provides real-time data transmission to different remote locations and, as a result, has the advantage of warning a large number of nuclear power plant operators and different stakeholders such as regulatory authorities around the world. The integration of artificial intelligence features with mobile computing features into nuclear power plant systems is an innovative idea that aims to increase the safety and reliability of nuclear power and enhance the decision-making process through intelligent predictive systems. The present work is the first scientific paper that examines the integration of AI and mobile computing together in nuclear power plant systems.

Figure 1 illustrates the structure of this article and highlights the main application of mobile computing and artificial intelligence in nuclear power plants. The first part of this paper highlights the nuclear power plant data sources and the different modern AI algorithms used in the context of NPP, such as the artificial neural network (ANN), the genetic algorithm (GA), etc. The second part focuses on the history of using smart devices in nuclear systems and the architecture of AI-powered mobile computing networks. The third part emphasizes the application of artificial intelligence and mobile computing in nuclear power plants. Subsequently, the last part of this paper delves into the features and challenges associated with the integration of AI and mobile computing into future applications within nuclear power plant systems.

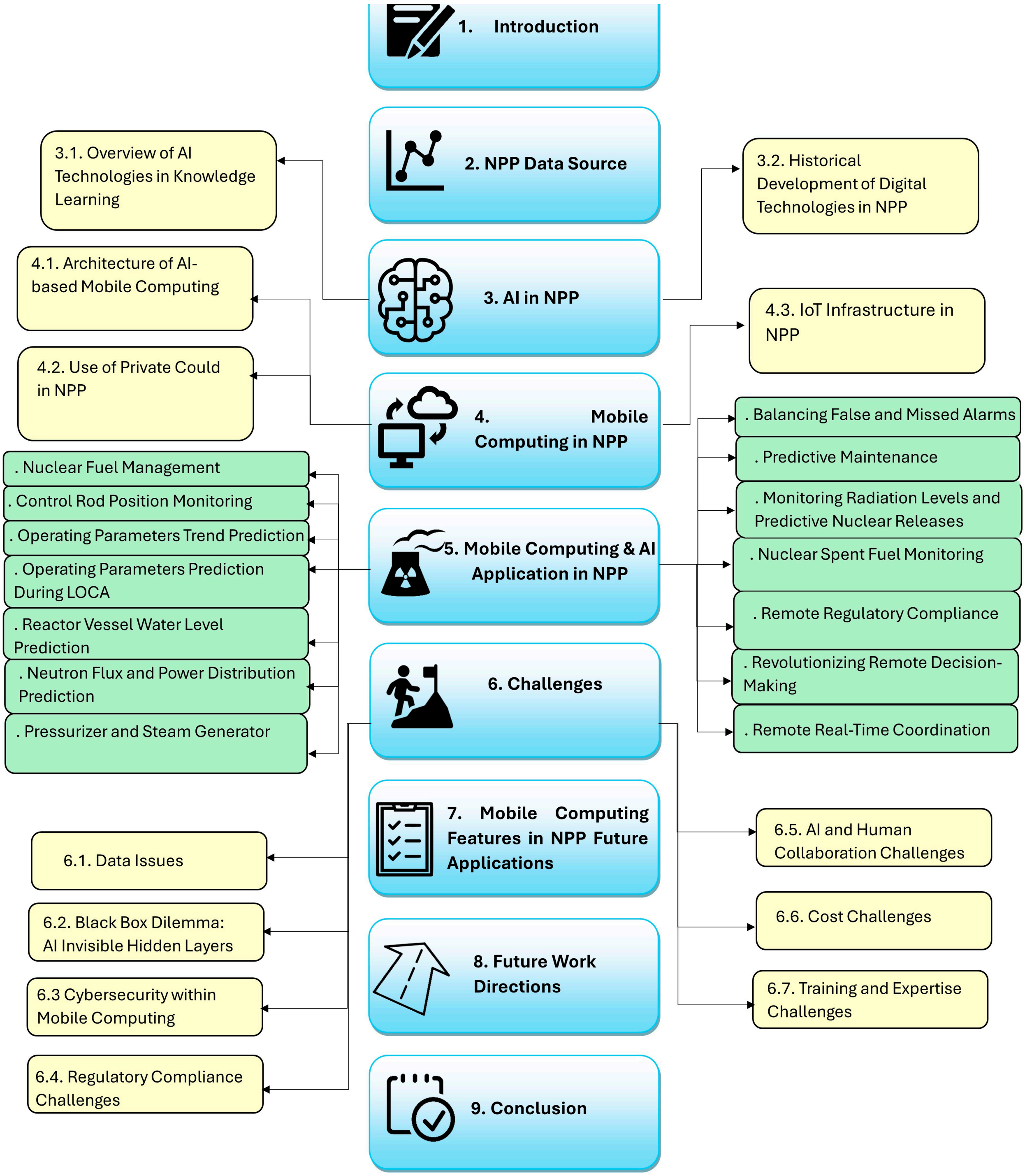

Figure 1. Article structure.

2. Nuclear Power Plant Data Source

The data on nuclear power plants (NPPs) come from mathematical modeling software, experiments, and plant sensors and are divided into four main categories, as mentioned in Figure 2. Regarding NPPs, the first-principles approach based on fundamental physical laws is used in mathematical modeling, which provides the necessary important and easily accessible data, especially when real-world observations are limited. In this case, the models can reproduce the behavior of NPPs during safe operation and accident scenarios, and operator training and plant safety analysis are the results of these models.

However, the challenges of this process are the accuracy and simplicity of the development of mathematical models of NPPs due to their nonlinearity [2].

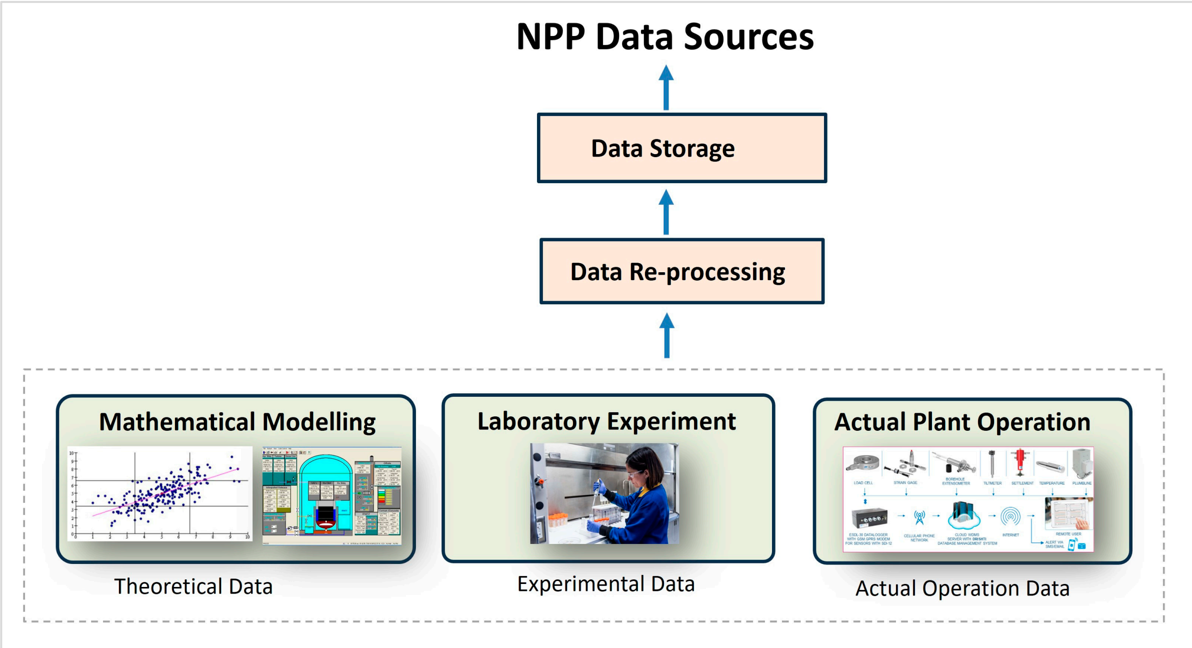

Figure 2. NPP data source.

The data on NPPs can also be retrieved from software platforms, such as the RELAP5 thermal-hydraulics code, which is used to model the coupled behavior of primary and secondary systems under different operational conditions. These applications facilitate the prediction, assessment, and monitoring of NPPs; however, the availability and accessibility of the data may be affected by security restrictions, regulations, and user permissions. NPP data also come from the experimental data collected in nuclear engineering laboratories by creating a robust and comprehensive dataset with their specialized equipment. Experiments are flexible and can be used in various research areas and for the nuclear industry as well [2]. Furthermore, in NPPs, sensors are installed that are able to generate data in real time and, hence, continuously provide a great volume of it. The sensor data help to provide mathematical models that are based on sub-systems, which include feedback loops and are continuously fed by real-time data, making it possible to estimate and control reactor variables such as the core outlet temperature and control rod position [2]. However, in some cases, the data can be collected through manual, labor-intensive processes, limiting its use beyond its initial purpose [3]. To improve efficiency and decision making, there is a growing focus on automating data collection and increasing data fidelity [3]. This involves transitioning from manual and analog forms to automated digital methods, enhancing the accuracy and timeliness of data across various sources within the plant [3].

By merging AI and mobile computing within NPP data sources, operators and researchers are able to have a better apprehension of the system's behavior, which is a stepping stone to making correct decisions by predicting and monitoring the overall plant's behavior in real time.

3. Artificial Intelligence (AI) in Nuclear Power Plant

3.1. Overview of AI Technologies in Knowledge Learning

The main point of the artificial intelligence (AI) field is that it deals with the digital representation of brain power in the form of software and other computing activities. A particular example of AI is machine learning (ML), which mainly concerns the smart ability of a device or a process to make use of the knowledge that it has obtained from data and to perform functions such as prediction and classification [4].

Artificial intelligence can be divided into supervised, semi-supervised, and unsupervised types. The identification of the models is said to be supervised when their regular behavior is labeled as accurately as possible with new inputs. Unsupervised learning is focused on unearthing patterns from unlabeled data. In reinforcement learning, thus far, agents must find the strategies that bring the highest benefits and determine what they can do to reach the required goals through interactions with the environment [4]. There are several ML techniques, such as linear regression, support vector machines, random forests, and artificial neural networks, which are buzzwords in the nuclear sector. However, the identification of the top feature pattern in ML often incurs high costs, which is a key drag factor. Deep learning (DL) has been used to approach this problem and is now a popular machine learning branch. It uses advanced computing technology and optimization techniques to train intelligent machines. DL-based models such as deep neural networks, convolutional neural networks, and recurrent neural networks are the default and are now proliferating in data-intensive domains [4].

Besides ML and DL, Evolutionary Algorithms (EA) have undergone tremendous development in the nuclear energy field. Figure 3 illustrates the different AI algorithms that are used in the case of nuclear power plant research. Methods such as genetic algorithms, ant colony optimization, and particle swarm optimization play significant roles in solving the complex, nonlinear optimization problems that are often met in nuclear reactor design and operation [4]. The access interfaces for these AI methodologies, accompanied by the increasingly immense databases of nuclear power plants, are more inclined to take the lead in the overall understanding, simulation, and optimization of nuclear power systems. [4]. Artificial intelligence technologies are transforming knowledge learning in the nuclear industry, offering advanced methods for data-driven decision making and operational efficiency [5]. Recent advancements in AI provide new opportunities for enhancing the accuracy and effectiveness of knowledge systems within nuclear power plants [5]. Furthermore, recent studies, such as the Idaho National Laboratory's exploration for the Nuclear Regulatory Commission, have highlighted the potential of advanced AI and ML algorithms to enhance nuclear plant safety, efficiency, and risk assessment through applications in reactor system design, plant operation and maintenance, and accident diagnosis and prognosis [6].

3.2. Historical Development of Digital Technologies in NPPs

The historical development of digital technologies in nuclear power plants has been shaped by the gradual evolution from analog instrumentation and control (I&C) systems to advanced digital systems, driven by technological advancements, equipment obsolescence, and the need for improved safety and operational efficiency [7]. Moreover, mobile computing relies on smart device employment within multiple systems and interfaces. From the 1980s up to now, the use of smart devices in the systems of nuclear power plants (NPPs) to address safety has been taken into consideration due to the emergence of several new issues. Smart devices represent a plethora of benefits that make them the most convenient solution for NPPs [8]. For instance, smart devices such as wireless sensor networks (WSNs) have emerged as a key technology for real-time monitoring in nuclear power plants, offering solutions for gathering and processing critical data. The development and applications of WSNs in NPPs are part of a broader trend that has seen smart devices increasingly integrated into various sectors, including military, environmental, and industrial fields [9].

Smart computers can deal with the replacement of outdated analogy devices, as the producers are turning their production toward these more flexible digital ideas that can be used in a wide range of industrial applications. Smart devices can integrate multiple separated analog parts into one unit, ensuring safety and, at the same time, reducing the risk of possible failures [8].

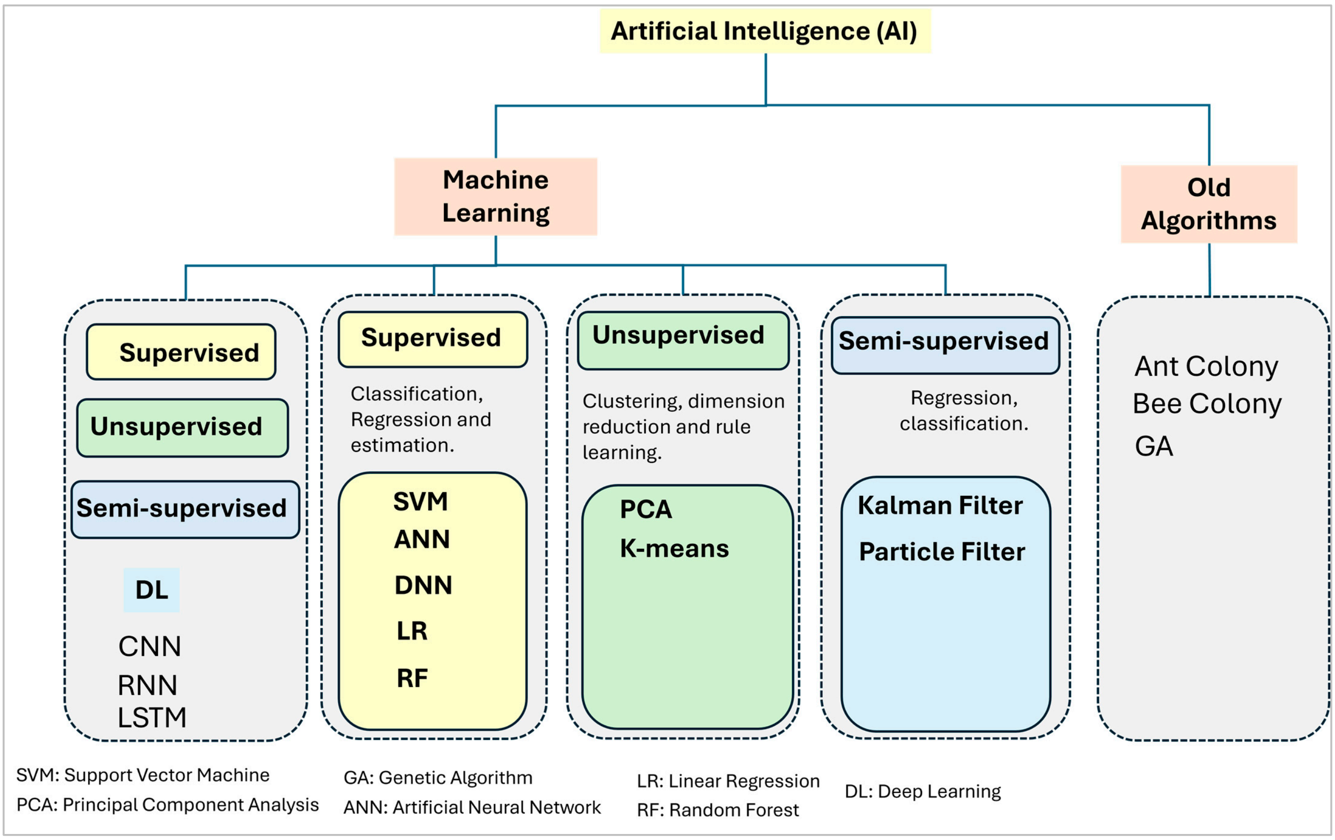

Figure 3. Summary of modern AI algorithms used in NPPs.

Looking further ahead, smart computers have extra smart diagnostics that can rapidly recognize and then report random outages; hence, quick maintenance can fix them, and safety-critical systems are switched on most of the time. This can decrease both operational and maintenance costs as the diagnostic system may include built-in diagnostics so there may be no need for surveillance tests at regular intervals. Further, smart tools can provide more sophisticated protection and monitoring functions, like the inclusion of complex trip set points and machines as well as electrical system condition monitoring. This, in turn, would improve the operating margins and safety margins, paving the way for nuclear power to see robust reliability and performance [8].

Although the integration of smart devices can require significant investment in training and logistics for staff, the long-term benefits in terms of increased reliability, availability, and operating flexibility make them a strong strategy for modern and intelligent nuclear power plants [8].

4. Mobile Computing in Nuclear Power Plants

4.1. Architecture of AI-Based Mobile Computing

The integration of AI with mobile computing, particularly in the context of advanced network technologies like 5G, presents significant advantages in real-time data processing and security [10]. The architectural framework for AI-powered mobile computing includes three main components, which are perception, cognition, and decision, as mentioned in [11]. The perception component is an area that acquires a great deal of information from a number of different channels such as mobile terminal data (MTD), radio access network data (RAND), and packet core network data (PCND). These data provide detailed information about user equipment, radio propagation environments, and mobile network elements, thereby the network can be globally understood regarding its state and condition. Cognition is the component that utilizes this massive amount of data to learn and extract valuable insights, for example, user preferences, mobility patterns, and traffic behaviors. The relationship between user traffic and the network state is also evaluated, which provides a deeper insight into the behavior of the mobile network. This information can be utilized in various sectors including nuclear power plant monitoring and control [11].

For instance, in a nuclear power plant, an AI-powered mobile computing architecture could be introduced in order to improve safety through enhanced efficiency. As a result of that, the perception component would collect data from the sensors monitoring the temperature, pressure, and radiation levels of the plant. The cognition system will, in turn, analyze this information, after which the system will proceed to find patterns and possibly detect anomalies, which would be a clear warning of an upcoming issue or failure. Based on this analysis, the decision component could be used either to send an alert in real time, schedule preventive maintenance, or adjust plant operations autonomously so that safety and stability are maintained [11].

By closing the loop between perception, cognition, and decision, the proposed architecture enables mobile network operators, as well as other industries, to effectively leverage AI and big data to enhance the planning, optimization, operation, and management of their systems. It is through this integrated AI mobile technology that we may see a huge migratory move to this technology in the nuclear power industry, as it is able to outperform, provide reliable service, and ensure safety in numerous applications [11]. In essence, the AI-based mobile computing architecture enables mobile devices to learn, adapt, and act autonomously by leveraging AI technologies [12]. However, while this architecture holds great potential for enhancing mobile applications, significant gaps remain between the current performance and users' Quality of Experience (QoE) expectations [12].

4.2. Use of Private Cloud in Nuclear Power Plant

In the context of nuclear power plant applications and mobile computing, the utilization of a private cloud infrastructure offers several compelling benefits compared to a public cloud approach. The first and most obvious, more extended control and governance, is related to the advantages of a private cloud for the organization [13]. Within a private cloud, a single entity governs the infrastructure policies, enabling the NPP to have a very central point of control over major concerns in security, manageability, privacy, audit, compliance, and governance [13]. This level of control is most critical for sensitive NPP applications and data, in which stringent regulatory requirements and considerations of data privacy are of paramount importance [13]. Furthermore, the private cloud model should allow easy portability of workloads and data between the internal and external data centers and increase the flexibility of the NPP in terms of the optimization of resource use in response to demand [13]. This is useful for mobile computing and AI applications since their use cases often require dynamical computing resource allocations versus fluctuating volumes of workloads and data processing [13].

The private cloud solution should, therefore, have the following basic characteristics, which will address the special requirements expected of NPP applications: a provisioning engine with automated infrastructure provisioning capabilities; workflow-driven mechanisms on approval for governance; user management and integration with enterprise authentication systems; an enterprise policy enforcement regime for resource allocation; and the ability to template capture standard patterns for common deployments, which enables self-service, automation, and a dramatic reduction in the time-to-market of new services and applications [13]. In addition, the private cloud provides monitoring, metering, and chargeback mechanisms that must offer end-to-end visibility in the use of various services, thus allowing an NPP to properly grab control over cost and resource utilization [13]. The private cloud should also support Service-Level Agreement (SLA) management, patch management, reporting, and incident management to guarantee reliability, availability, and performance for all mobile computing and AI-powered applications in use by the NPP [13]. In reference [14], the implementation of reliable cloud solutions in nuclear power plants, such as the NasCloud platform, enabled secure, cross-platform access to critical simulation tools, allowing for multi-user collaboration and training in nuclear safety analysis across time and space, while ensuring scalability, high concurrency, and robust security in sensitive applications like accident simulations. Furthermore, the use of private cloud computing in nuclear power plants provides a secure and efficient platform for nuclear design and safety evaluation [15]. By leveraging advanced features such as secure data storage, controlled access, and high-performance computing, private cloud solutions like SuperMC Cloud address the specific demands of nuclear simulation, enabling faster processing, enhanced data security, and improved collaboration among geographically dispersed teams [15].

Therefore, private cloud infrastructure is potentially an extremely attractive proposition for NPP applications and mobile computing against regular public cloud solutions. Figure 4 depicts a typical private cloud infrastructure. The level of operational control, governance, and tailored capabilities that the private cloud will offer will much better align with the very rigorous requirements of the nuclear industry, ensuring the secure and efficient deployment of mission-critical applications and services.

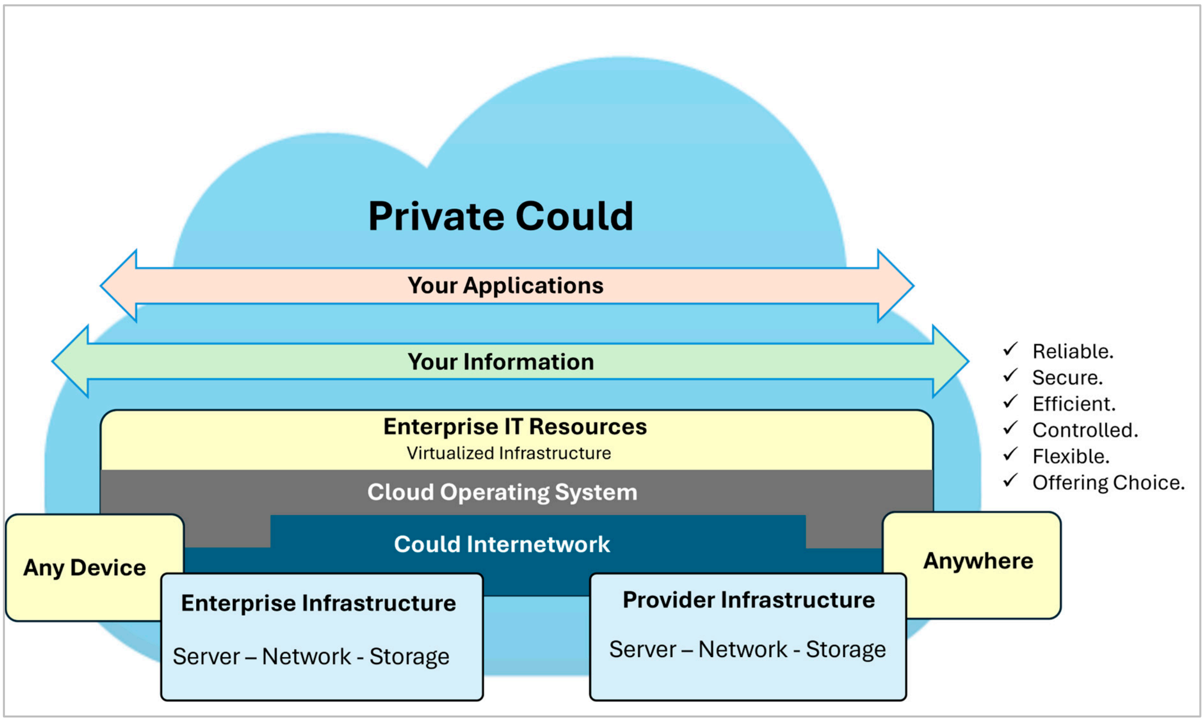

Figure 4. Formation of private cloud [13].

4.3. IoT Infrastructure in Nuclear Power Plant

In the near future, IoT technology, accompanied by artificial intelligence and blockchain, will quickly change the whole way of working in industrial and business sectors. Indeed, data collection by IoT devices would be of no value if there were no analysis and decision making based on these data, which is why we need to combine AI with IoT devices [16]. The use of these systems would be beneficial when coupled with AI, as IoT allows data collection and, henceforth, a better understanding of processes of nuclear power plants and monitoring, supporting the decisions needed during operation and also during critical accident scenarios [17]. Furthermore, given that nuclear power plants need constant optimization and monitoring for reliability and safety, the use of IoT may provide data for pointing out possible failures in advance, thus enabling interventions in good time for refurbishment and, thus, safety and security. The possibility of obtaining analytic and monitoring flexibility of the overall plant is also afforded by remote data collection and transmission [17]. However, nuclear power plants need to embed a certain infrastructure in order to be able to use IoT and benefit from it. The high-level IoT infrastructure required in the case of NPPs includes IoT devices, connectivity, and sensors so that the data can be collected and transmitted effectively, as illustrated in Figure 5. Furthermore, the infrastructure of the IoT in nuclear power plants should include a secure data transmission line, as well as a secure data storage interface to mitigate any cybersecurity risks that may arise from this application [17].

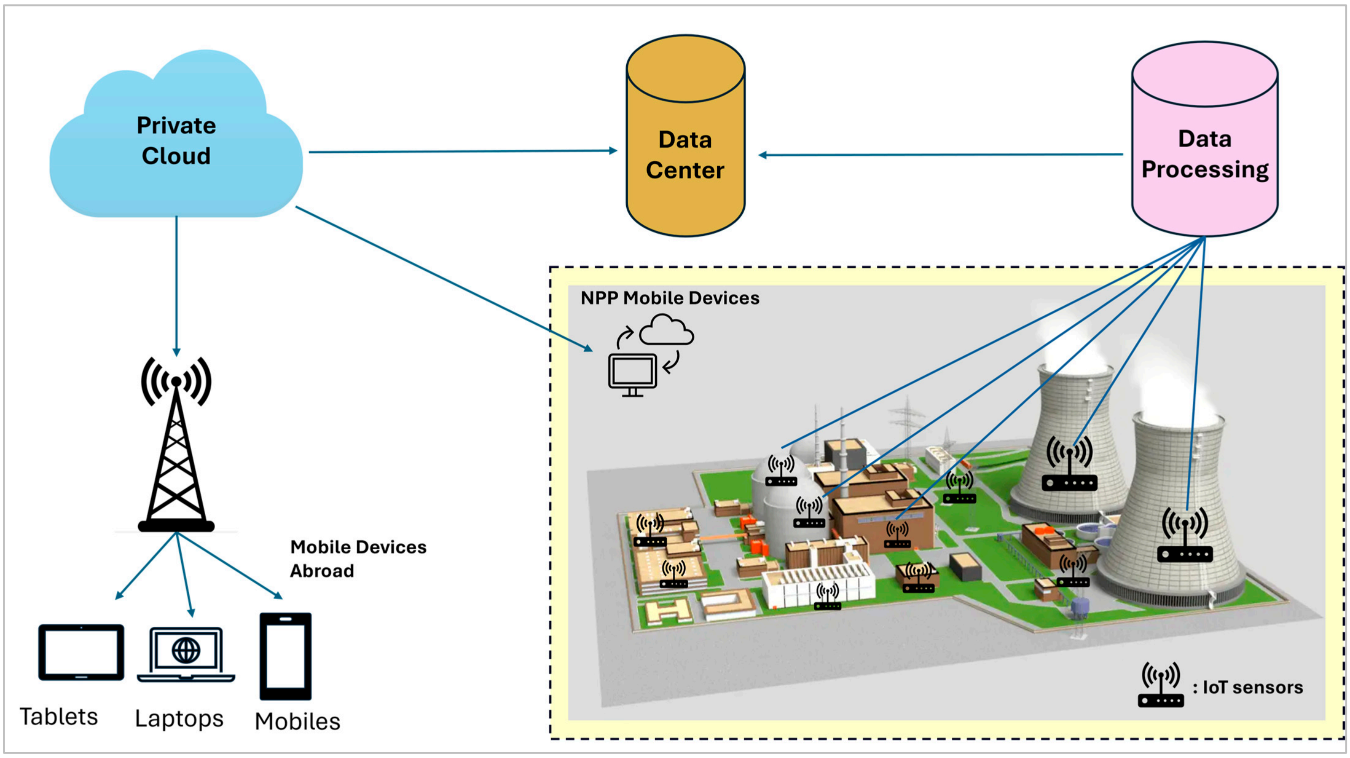

Figure 5. Modeling of IoT infrastructure in nuclear power plants.

5. Mobile Computing and AI Application in NPP

The concept of using artificial intelligence and mobile computing in nuclear power plants is based on the predictive capabilities of AI algorithms and the real-time data transmission capabilities of mobile computing as mentioned in Figure 6.

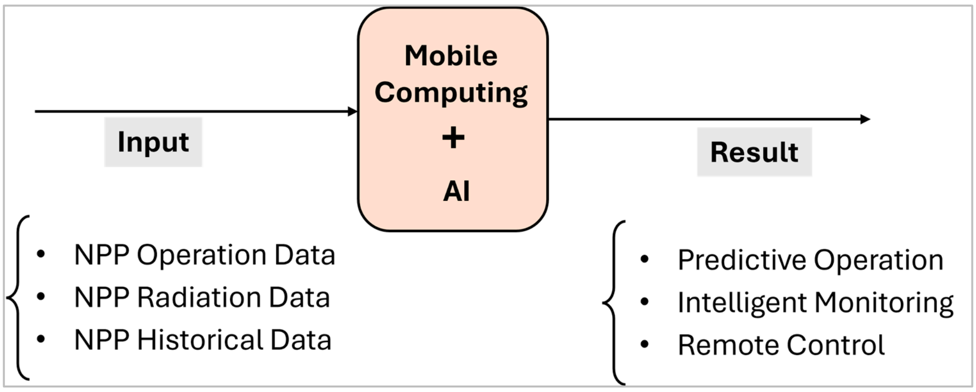

Figure 6. Concept of using AI and mobile computing in NPPs.

All the reviewed applications of artificial intelligence in nuclear power plants are summarized according to the AI algorithms used, suggested mobile computing architecture, and references in Table 1.

Table 1. Reviewed AI algorithms in NPPs and suggested mobile computing architecture.

NPP Life Cycle	Application	AI Algorithm Used by Reference	Suggested Mobile Computing Architecture	Reference
Design	Nuclear Reactor Core Design	Multi Objective GA, Parallel GA	-	[4]
	Thermohydraulic Simulation and Analysis	DL-based ROMs	-	[4]
	Radiation Shielding Design	GA, MACNOS	-	[4]
Operation and Maintenance	Nuclear Fuel Management	GA, ANN, PIMLAF, Ant Colony	ML-based Sensors, Mobile Devices	[18]
	Control Rod Position Monitoring	Radial Basis Function NN, Levenberg-Marquardt	CRMS Sensors, Remote Cloud	[19]
	Operating Parameters Trend Prediction	Neuro-Fuzzy, BPNN	IoT Sensors	[20]
	LOCA Operating Parameters Prediction	Feedforward DNN, Long-short Memory Algorithm	IoT sensors, Mobile Devices	[21]
	Reactor Vessel Water Level Prediction	DNN, GA	ML-based Sensors, Mobile Edge Cloud	[22]
	Neutron Flux and Power Distribution Prediction	ROM-ML	ML-based Sensors, Embedded Mobile Devices	[23]
	Pressurizer And Steam Generator Fault Diagnosis	Unsupervised Clustering, Fuzz C-Means, ANFIS	IoT sensor, Mobile Devices	[24,25]
	Balancing False and Missed Alarms	AAKR, CA, GA	ML-based sensors, Remote Cloud	[26]
	Predictive Maintenance	LR, SVM	IoT sensors, Mobile Devices	[27]
	Monitoring Radiation Levels and Predictive Nuclear Releases	ML, DL, ANN	ML-based radiation sensors, Mobile Devices	[28]
	Remote Decision Making	AI Algorithms (suggested)	IoT sensors, Mobile Devices, Remote Cloud	-
	Remote Regulatory Compliance Monitoring	AI Algorithms (suggested)	IoT sensors, Mobile Devices, Remote Cloud	-
	Realtime Coordination During Large Nuclear Accident	AI Algorithms (suggested)	IoT sensors, Mobile Devices, Remote Cloud	-
Waste Manage ment	Nuclear Spent Fuel Monitoring	LR, SVM	ML-based radiation sensor, Mobile Devices	[28]
	Nuclear Waste Safeguarding	LR, SVM	ML-based radiation sensor, Mobile Devices	[28]

5.1. Nuclear Fuel Management

Artificial intelligence and mobile computing are two powerful tools that are able to enhance nuclear fuel management during the operation of nuclear reactors. While AI can analyze and predict high-level fuel parameters from the embedded sensors in the reactor core, mobile computing offers the opportunity for real-time monitoring and remote access to these data. Several applications involve promising AI and mobile computing tools in the field of fuel management. For instance, refs. [29–32] used a genetic algorithm to optimize nuclear fuel management and loading patterns, whereas [33,34] used the ant colony algorithm to optimize and predict fuel burnup in a Boiling Water Reactor (BWR). In Refs. [18,35,36], the authors demonstrated the use of AI algorithms to predict the critical heat flux and temperature values at the wall using an artificial neural network (ANN) and a physics-informed machine learning-aided framework (PIMLAF). The fuel optimization provides AI-based predictions for burnup patterns based on previous data, and the mobile computing feature provides an enhanced reloading schedule reminder. This typical feature might be of more interest in developing countries with new nuclear facilities installed and less experience in licensing and regulations; thus, AI and mobile computing in fuel management would serve as very helpful tools for nuclear agencies to monitor the operation of these facilities and receive an instant notification for any predicted fuel issues. Added to that, AI-based mobile computing enhances the security of nuclear fuel by enabling the remote monitoring of nuclear fuel storage, especially in remote locations such as small modular reactors (SMRs), which increases the safety and security of nuclear fuel and decreases the non-proliferation risk.

5.2. Control Rod Position Monitoring

The control rod plays a crucial role in the safety and operation of the nuclear reactor. In the meantime, the measurement of the control rod position is conducted by the control rod position measurement sensor (CRMS), which concerns the start-up, power regulation, and shutdown of the nuclear reactor. However, there is still a lack of research on comprehensive reviews of the state of progress of the CRMS of nuclear reactors [37].

The application of AI together with mobile computing offers a tremendous opportunity to enhance the monitoring of the position of the control rod. In reference [19], the author used the radial basis function neural network, Levenberg–Marquardt, and a group data-handling methods to monitor the position of the rod from the in-core neutron flux measurements. The implementation involved an AI algorithm and mobile computing to monitor the control rod in the nuclear reactor and would also involve IoT sensors, data collection, wireless data transmission, and an AI algorithm to monitor and predict the control rod position. This feature is very important in an operated nuclear power plant not only because it increases safety but also because it increases the reliability of the plant with continuous production by avoiding control rod position issues.

5.3. Operating Parameters Trend Prediction

The use of AI and mobile computing in the normal operation of nuclear facilities provides the possibility to detect the failure of any equipment or any incorrect sensor measurement when the prediction results deviate from the actual measurement results [38]. In a previous paper, the author [38] used a neuro-fuzzy technique to predict the operating parameters of a nuclear power plant, whereas another author [20] used a dynamic back-propagation neural network (BPNN) as an AI algorithm. These parameters include different operating data such as temperature, pressure, radiation levels, coolant flow rates, etc., which are very crucial for the safety of the plant and its availability.

By implementing AI algorithms, the system can predict trends in operating parameters by learning from historical and operating experience data; for instance, forecasting potential equipment failures or deviations from normal operating conditions. The integration of mobile computing with AI would provide an opportunity for alert systems that notify operators whenever the AI algorithm detects abnormal trends in the parameters. Thus, mobile computing plays a crucial role here by delivering alerts to smart devices, allowing for quick response and informative decision making.

5.4. Operating Parameters Prediction During LOCA

Loss of coolant accident (LOCA) is a design-based accident in nuclear power plants. This accident includes a break in the cold leg, hot leg, and other associated pipelines of the reactor, which induces a loss of the coolant and an increase in the temperature of the fuel and constitutes an increased risk of melting the fuel and threatening the safety of the plant. Artificial intelligence and mobile computing can be used in this context to predict LOCA scenarios before they happen and send real-time data to the operator and regulator authority to help prepare response strategies beforehand. As the mobile computing feature allows the transmission of data, the international nuclear authority overseas would have the opportunity to receive the LOCA scenario data in real time, which allows full control and containment of any LOCA-related incident. This feature is very helpful, especially in countries operating NPPs for the first time with less experience.

At the moment of writing this article, many works have been conducted on the use of artificial intelligence algorithms in LOCA scenarios. Figure 7 illustrates and models the concept of using AI and mobile computing to predict the operating parameters during a loss of coolant accident in nuclear power plants. In reference [21], the author used a feedforward deep neural network and long-short memory to train and predict the LOCA scenario in a nuclear power plant using four different parameters, namely, the peak clad temperature, core pressure, break flow rate, and water level.

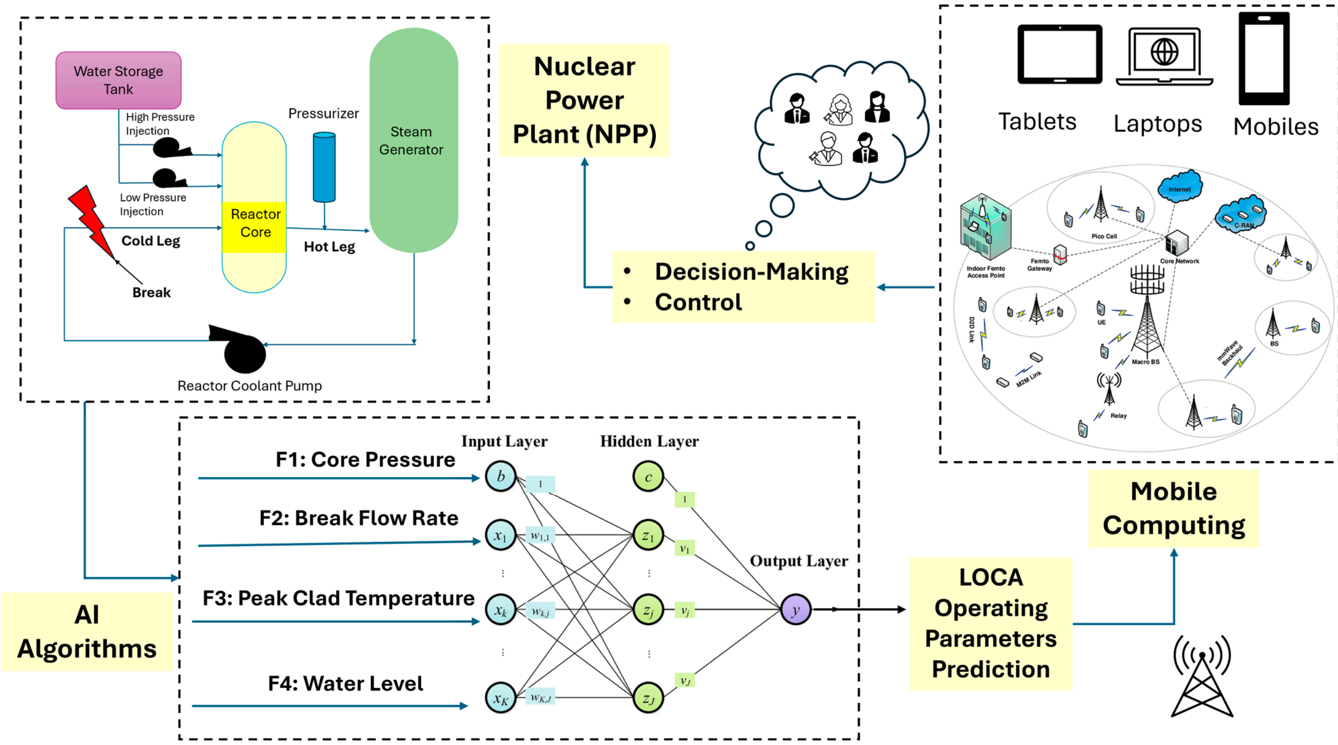

Figure 7. Modeling of AI and mobile computing application during LOCA in NPPs.

5.5. Reactor Vessel Water Level Prediction

Obtaining data generated from NPPs is crucial to preserve reactor integrity and mitigate accidents and serious accidents. Nevertheless, several safety-critical data signals from nuclear power plants cannot be perfectly measured due to sensor degradation or failure under serious accident circumstances. One crucial piece of reactor data is the reactor vessel (RV) water level, which is very important in case of an accident because it is directly related to reactor cooling and the prevention of core exposure [22].

Sometimes, during challenging conditions, this parameter is hard to monitor for several reasons; hence, the use of artificial intelligence and mobile computing in this area would enable real-time RV water level prediction and transmission using multiple smart devices. Therefore, in the case of a failure to obtain data on the RV water level directly from the sensor, the AI algorithm could estimate the water level using data from other relevant reactor parameters and conditions during the incident. The use of mobile computing offers the opportunity for this parameter to be interpreted and analyzed by different nuclear authorities. Added to that, it will help in keeping a record of these data for the implementation of future training and accident mitigation strategies.

In reference [22], the author predicted the RV water level using deep neural networks where the data were obtained by simulating the postulated loss-of-coolant accidents at hot and cold legs and steam generator tube rupture using a modular accident analysis program code. It is important to note that only in case of an accident is the monitoring of the RV water level critically important for preventing the core from melting. The author also used another AI algorithm, the genetic algorithm, to optimize the DNN model [39] for RV water level prediction by optimizing the selection of the numbers of hidden layers and nodes [22].

5.6. Neutron Flux and Power Distribution Prediction

The nuclear reactor is a complex physical system that generates electricity. The generation of nuclear energy is realized under very high safety standards where strict criteria must be fulfilled at the design and operation levels. What is fundamentally required is precise knowledge of important quantities such as temperature, neutron flux, power, radiation level, etc. The quantities can be overall outputs, e.g., maximum temperature, average temperature, total generated power, etc., but the knowledge of more complete information such as temperature, flux, and power maps for the whole reactor might also be required for reliable NPP operation [23].

This knowledge can be attained through measurements, simulation, and, more recently, artificial intelligence. The use of AI algorithms and mobile computing can significantly improve the measurement of neutron flux and lower distributions within the reactor core. Furthermore, while AI algorithms can collect data from various sensors within the reactor, e.g., neutron detectors, temperature, pressure gauges, etc., mobile computing can facilitate real-time data collection and transmission from the sensor.

Some techniques can be used to reduce the dimensionality and extract features from these data to improve the dataset's quality and relevance. The deployment of AI models and mobile devices allows for real-time neutron flux and power distribution prediction, which in turn allows for quick decision making by the designated authorities and the remote monitoring capabilities of these two parameters. This AI and mobile computing feature of neutron flux and power distribution would offer a tremendous opportunity in the future for regulation authorities to inspect nuclear facilities at any time and at any place in the world to ensure that the operation of the plant aligns perfectly with the safety regulations and the operational guidelines of their license. A different AI algorithm was proposed to predict the neutron flux and power distribution in a nuclear reactor core. In reference [23], the author used ROM-ML to predict, using high-dimensional outputs, the neutron flux and distribution of power in a simulated reactor core.

5.7. Pressurizer and Steam Generator Fault Diagnosis

The pressurizer is a very important component in the nuclear power plant operation, as it regulates the heat transport system. Any deviation or incorrect data from this component will result in variations in the operating conditions for a reliable plant. Artificial intelligence such as machine learning could be employed in the detection of any deviation or anomalies in the operating condition of the pressurizer. Data collection and training using historical data have great potential for predicting the faults that may happen within the pressurizer in a nuclear power plant. The integration of mobile computing within the AI system enables mobile devices to receive predictions from the AI algorithm and alert operators in the main control room in real time, resulting in proactive pressurizer control. In the event of pressurizer faults, the plant may require shutdown to ensure safety. Different AI methodologies can be used for fault detection within the pressurizer. In his paper [24], the author used an unsupervised clustering methodology for pressurizer transient prediction, as well as a Fuzz C-Means algorithm to optimize the interpretation and the determination of fault causes and origins.

The steam generator (SG) is the heat sink of the nuclear reactor and it generates the steam that rotates the turbine for power generation. A deviation in one of the steam generator's parameters results in anomalies within the reactor core as well as anomalies in the balance of the plant (BOP). The use of artificial intelligence and mobile computing to monitor and predict steam generator anomalies would result in increased plant safety and stable power generation. IoT sensors can be employed to collect real-time data on temperature and pressure from the steam generator. AI algorithms can be trained to detect and diagnose faults within the SG parameters and, if necessary, propose alternative components, although it is important to note that the SG cannot be isolated during normal power operation. The use of mobile computing within AI for SG fault diagnosis provides the opportunity for remote assistance and quick decision support.

Several AI algorithms can be used to predict faults within the steam generator in nuclear power plants. In his paper, ref. [25], the author used an Adaptive Neuro-Fuzzy Inference System (ANFIS) to predict and diagnose the steam generator transient within the nuclear power plant by predicting data for the steam outlet pressure, steam generator water level, and rupture pressure severity.

5.8. Balancing False and Missed Alarms

In a nuclear power plant, balancing false alarms and missed alarms is vital for the continued safety of the plant as well as for efficient operation. The integration of artificial intelligence and mobile computing would play a significant role in attaining this balance. Furthermore, AI algorithms can be trained using historical plant data for false alarms in order to recognize different patterns of normal operations versus anomalies with real issues. Additionally, by employing AI models within nuclear power plant systems, the detection of any deviation would be easily predicted and recognized, which reduces false alarms. AI models are also able to predict equipment or sensor failures before they happen, which results in reducing the likelihood of false alarms triggered due to equipment deterioration. The integration of mobile computing with AI enables real-time monitoring and collaborative decision making with regard to the alarms by involving different team members remotely and ensuring an efficient response to the alarm, therefore reducing the risk of missed alarms.

Various AI algorithms can be used to balance false and missed alarms within nuclear power plants. In his paper [26], the author used an Auto-Associative Kernel Regression (AAKR) algorithm as well as a hybrid approach based on Correlation Analysis (CA) and a genetic algorithm (GA) as an AI algorithm to balance the alarm occurrences in an NPP.

5.9. Predictive Maintenance

Nuclear power plants operate under high safety and reliability requirements and integrate critical infrastructure systems that require the collection of real-time data to ensure effective and secure operations. Furthermore, in order to be cost-effective, NPPs have to run at maximum capacity with minimal interruptions. Therefore, it is necessary to maintain plant equipment in optimal condition so that NPPs can achieve higher availability and reliability. However, maintaining the equipment increases the operating cost considerably, and the solution to this problem is to implement corrective and predictive maintenance of the NPP's components [27].

Artificial intelligence and mobile computing can be employed to address this issue by installing IoT sensors on the equipment to collect real-time data on different nuclear power plant parameters, such as the temperature on the pressure tube to avoid creep and other temperature- and pressure-related issues. AI algorithms can be utilized to analyze the data collected and predict effective maintenance needs and schedules based on the generative AI model. The integration of mobile devices allows maintenance staff to receive alerts for timely intervention. Different machine learning can be employed in predictive maintenance, such as support vector machine (SVM) and logistic regression (LR) models [27].

5.10. Monitoring Radiation Levels and Predictive Nuclear Releases

Nuclear energy has significant potential; however, it also poses significant security risks, therefore efficient radiation detection technology with support from artificial intelligence (AI) systems is vital [28]. Furthermore, there is increasing concern that acts of terrorism may attempt to detonate a nuclear weapon. For those reasons, there is a continuous quest to invent novel analyses and systems (i.e., artificial intelligence-driven detection and tracking) that can find nuclear materials being produced or transported between facilities/to their destinations [28].

By means of AI technology (i.e., machine learning (ML), deep learning (DL), and artificial neural networks (ANNs)), it is possible to develop radiation-detection algorithms that leverage cutting-edge technology in multimode data fusion, machine learning, sensor networks, mobile computing, and big-data analytics [28]. The implication of radiation-detection technology becomes apparent in this complex environment as a key protector against nuclear threats [28]. Primarily, radiation detection is the observant guard responsible for detecting and measuring ionizing radiation. This radiation involves neutrons, gamma rays, and alpha and beta particles and has the potential to have both positive and negative effects [28].

Radiation-detection technology plays a fundamental role in nuclear threat reduction, acting as a crucial tool to safeguard against the proliferation of nuclear weapons and materials, avoid acts of nuclear terrorism, and monitor potential environmental risks [28]. Furthermore, AI algorithms can process vast amounts of radiation data from sensors and detectors with unparalleled speed and accuracy. This enables real-time analysis of radiation levels, identifying anomalies or potential threats more effectively than manual monitoring [28]. Additionally, AI algorithms based on machine learning and artificial neural network models can predict equipment failures in radiation detectors by analyzing historical data and sensor performance. This ensures that detectors are always operational and reliable [28].

Likewise, AI-powered robots can autonomously inspect and maintain radiation detectors in hazardous or hard-to-reach areas, reducing human exposure to ionizing radiation [28]. Moreover, AI algorithms can identify unusual radiation patterns or signatures, which may indicate tampering or the presence of illicit nuclear materials. This early warning system is essential for nuclear security [28].

The integration of artificial intelligence and mobile computing could revolutionize Radiation Detection. AI systems, powered by advanced algorithms and machine learning, can predict radiation levels for normal and safe operation. In the case of deviation or anomalies, the shift between the measured radiation levels and the levels predicted by the AI model would indicate potential issues that require immediate intervention. The use of mobile computing with AI features makes this intervention effective and quick, as mobile devices allow one to send real-time radiation levels to different team members, allowing for virtual assistance and collaborative decision making.

5.11. Nuclear Spent Fuel Monitoring and Safeguarding

Nuclear fuel is defined as fissionable nuclear material in the form of fabricated elements for loading into the reactor core of a nuclear power plant, and spent nuclear fuel is classified as radioactive waste consisting of uranium, TRU (transuranic actinides), and fissions products [40].

Artificial intelligence and mobile computing can be employed to ensure the safe monitoring and storage of spent nuclear fuel. AI can assist in monitoring spent fuel storage and transportation by analyzing data from security cameras, access logs, and environmental sensors. It can detect unusual activity or breaches in security protocols [28]. Furthermore, AI-driven predictive maintenance models can optimize the upkeep of spent fuel storage facilities, ensuring they meet safety and security standards [28].

On the other hand, mobile computing features can assist in handling and inspecting spent fuel casks, improving the efficiency and safety of storage and transport operations, while AI technology detects irregularities in spent fuel storage conditions, such as temperature fluctuations or unauthorized access, triggering immediate response protocols [28].

Additionally, AI can play a pivotal role in monitoring spent nuclear fuel storage facilities by combining data from security systems, environmental sensors, and access control logs and creating a holistic security overview of spent fuel facilities [28]. The combined features of mobile computing allow for the monitoring of all the spent fuel storage facilities around the world by means of smart remote devices and IoT sensors and cameras, which enhance the containment of nuclear material and decrease the non-proliferation risk related to nuclear waste weaponizing.

5.12. Remote Regulatory Compliance Monitoring

From the perspective of nuclear power plants, incorporating artificial intelligence (AI) and mobile computing can considerably advance regulatory compliance monitoring and inspection systems. AI algorithms can process widespread datasets collected from different sensors, control systems, and inspection reports, applying machine learning algorithms to detect glitches, predict equipment failures, and ensure a firm's adherence to regulatory safety standards. These intelligent models can recognize emerging patterns and trends indicative of potential compliance concerns, facilitating timely and practical interventions. Mobile computing improves these capabilities by permitting real-time data collection, transmission, and analysis directly on-site, thus raising the precision and efficiency of regulatory inspections.

Regulatory authorities benefit from this integration by obtaining the ability to continuously monitor all critical parameters of nuclear power plants, validating that operations conform to the safety guidelines specified in their licenses. Mobile computing permits inspectors equipped with advanced devices to access AI-driven diagnostics and analytics tools, streamlining the identification of non-compliance areas and enabling immediate corrective actions, thereby minimizing risks associated with delayed responses.

Furthermore, mobile computing features and real-time data transmission capabilities extend the reach of regulatory oversight, permitting authorities to remotely monitor and inspect nuclear facilities across the globe. This global oversight confirms that facilities maintain compliance with international safety standards irrespective of their geographic location. AI-generated reports, available on a daily, monthly, and yearly basis, provide comprehensive insights into the operational status and safety compliance of nuclear facilities. These reports facilitate regulatory committees to track adherence to protocols continuously, promptly address deviations, and maintain a high level of safety assurance. Therefore, the combination of AI and mobile computing not only improves the effectiveness of regulatory compliance monitoring but also improves the overall safety and operational reliability of nuclear power plants worldwide.

5.13. Revolutionizing Remote Decision Making During Serious Accidents

One of the most exciting things that the coupling of AI and computing technology of mobile devices can make possible is to support nuclear power plant monitoring and decision-making processes remotely. AI algorithms, in essence, consist of data analytics programs and programs that provide the plant with the critical data needed to have the plant perform as expected all of the time. Its deep learning component aids in the real-time analysis of vast amounts of data generated by sensors and monitoring devices at the plant, thus enabling the early detection of problems and ensuring the necessary preventive maintenance of the equipment. Moreover, the highly developed machine learning techniques can discern hidden trends and correlations in the data that can throw human detection off course, thereby making it possible for them to give their teammates a compatible analysis of the plant conditions and potential problems. Through the use of these AI capabilities, decision-makers can make both quicker and more positive responses given that they have all valid information, thus providing an environment of better decision making. Adding to this, mobile computing supports the idea by enabling the people who operate, manage, and maintain the plant to have access to critical information and AI-driven insights remotely. With the help of secure mobile applications, plant owners, employees, and decision-makers can view plant conditions from anywhere and obtain commands from the system, all through their mobile devices. The technology that encourages online access to the plant conditions can finally be considered a real-time technology with online surveillance systems, which will help in the dissemination of information, course reconfiguration, and the support of content expertise between geographically distributed teams. At the same time, electronic devices with digital reality might be used to visualize things like the location of objects that personnel have to inspect, which, in turn, would be displayed on the physical objects, thus enabling the best precision and the greatest efficiency.

Overall, the combination of AI and mobile computing technologies can significantly enhance remote decision-making processes in nuclear power plant operations. AI algorithms can analyze vast amounts of data from plant sensors and monitoring equipment in real time, enabling the early detection of anomalies, predictive maintenance, and optimization of operational performance. The training mechanism for AI, therefore, is based on dimensions like data analytics programs and programs required to satisfy the demand that the plant operates at a highly efficient level. The synergy between AI and mobile computing acts as a firm foundation for improving security, reliability, and efficiency in nuclear power plants. This technology plays a role in the adoption of quicker data-based decision making and influencing communication and collaboration, which leads to risk reduction and plant operation profit. This methodology of action addresses not only fast and short-term operating needs but also strategic planning and continuous improvement in nuclear power plant management in the near future.

5.14. Remote Real-Time Coordination during Large Nuclear Accidents

Integrating AI and mobile computing to deal with large-scale nuclear accidents from remote areas is an innovative feature that has really never been achieved anywhere. AI is capable of processing and analyzing a huge amount of data coming from many sources, sensors, radiation detectors, and satellite imaging that, in return, will provide the real-time status of the situation and predictive analytics. As a result, it will be possible to immediately recognize risks and make the right decisions. Further, as for mobile computing, its advantages include the possibility for first responders to reach out, share, and upgrade key data using their mobile phones, tablets, and other handheld devices, thus, guaranteeing smooth communication and coordination.

For instance, during the Fukushima Daiichi nuclear disaster in 2011 [41], communication breakdowns and the loss of plant monitoring occurred due to external disasters such as earthquakes and tsunamis, which caused a total power outage. While AI and mobile computing may not have prevented this particular incident, their integration could significantly enhance remote real-time coordination and data processing in nuclear incidents where power and communication systems remain intact. Among the issues experienced, failure in quick information collection, analysis, and dissemination was the leading factor, while such issues resulted in problems like missing evacuations, wrongful allocation of available resources, and failure of containment measures. In an alternative reality where AI and mobile computing were present, short-burning AI programs would have measured radiation doses and radiation spread and estimated the amount of damage to reactors in seconds. Simultaneously, mobile computing could have provided emergency responders and decision-makers with real-time updates, interactive maps, and coordination tools, enhancing situational awareness and enabling more effective and timely actions.

During such incidents, AI could use data to produce dynamic risk maps and thus optimize routes of evacuation, while mobile applications could offer direct communication between field teams and command centers. This union is not limited to the proliferation of disaster management but also finds applicability in the reduction in human exposure to radiation and the realization of protection measures, and, eventually, lessening the consequences of the disaster. The above dissemination of technology will ensure a smart, educated, and flexible response to the disaster, which will play a major part in safety, the redirection of resources, and encasement of the disaster, eventually taking into consideration public health and the environment in the case of a nuclear emergency. Figure 8 models the employment of AI and mobile computing during a large nuclear accident.

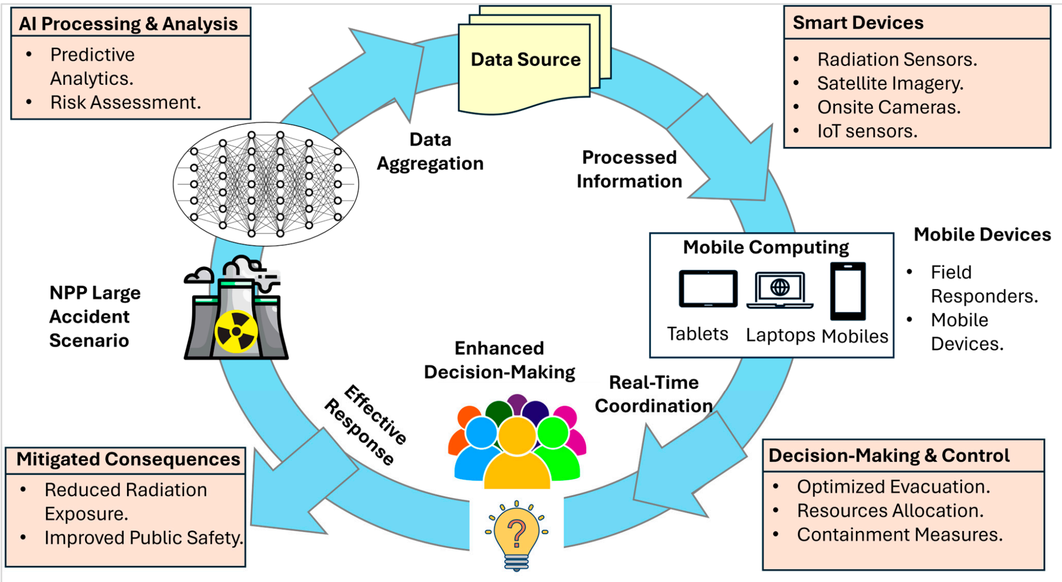

Figure 8. AI and mobile computing applications for remote real-time coordination during large nuclear accidents.

The literature reviewed here and summarized in Table 1 shows that artificial intelligence can be applied to a nuclear power plant's entire life cycle. In contrast, it seems that mobile computing is only used in operation phases and waste management. This is because, during the design phase when the nuclear power plant is not in operation, no real-time data will be available that would warrant the use of mobile computing technologies. One major finding is that AI can be employed broadly throughout the whole life cycle of a nuclear power plant, from detailed design to decommissioning and waste management, as shown in Figure 9. In contrast, mobile computing technologies apply only to operational and waste management stages since these stages involve the generation and transmission of real-time data that can be effectively tapped through mobile computing platforms.

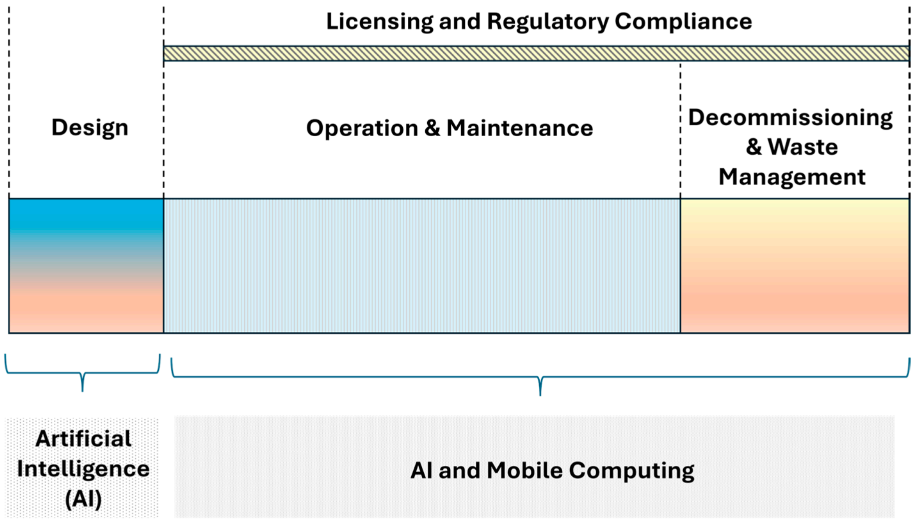

Figure 9. Application of AI and mobile computing throughout the lifecycle of NPPs.

6. Challenges

The use of AI technology in nuclear reactor research has been significantly boosted by machine learning (ML) and deep learning (DL). These innovative algorithms are able to predict nuclear power states and adjust the length of time between tasks, e.g., maintenance, etc., for the purposes of saving money and lowering the risk of nuclear accidents. Nevertheless, the use of AI-based approaches in the nuclear energy domain is still considered non-realistic due to scaling- and applicability-related issues. Figure 10 summarizes all the challenges and limitations that are associated with the use of AI and mobile computing in nuclear power plants.

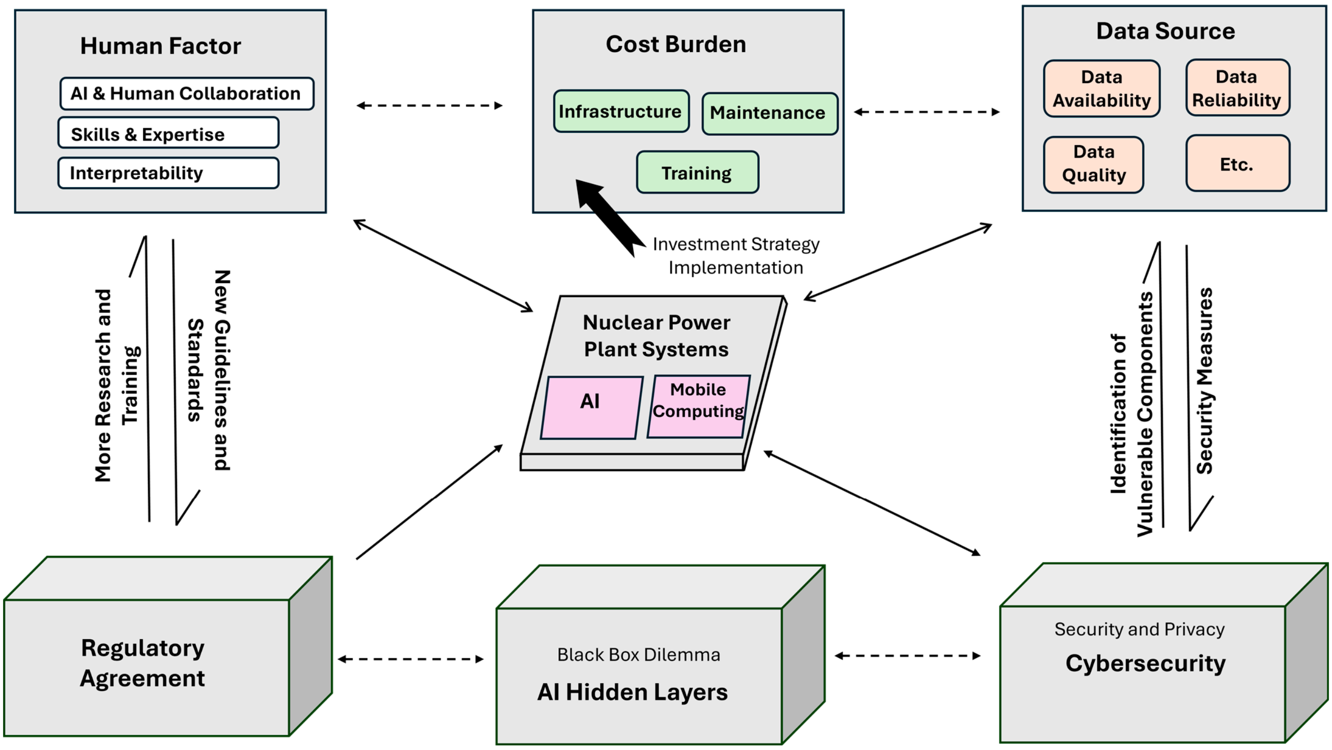

Figure 10. Challenges of using AI and mobile computing in NPPs.

6.1. Data Issues

Data sources and patterns represent one of the main issues of AI in nuclear power plants. These data problems involve issues of obtaining reliable experimental data due to the use of simulation datasets rather than those taken from real nuclear power plants (NPPs). The comprehensive undertaking of a simulated experimental study in an NPP is a very demanding process and is both costly and unsafe. Therefore, virtually all of the researchers working in this field have to rely on data records that are derived from simulated datasets rather than from real-world datasets. There is a discrepancy in the case of implicit data characteristics vis-a-vis real-world data with the incorporation of AI systems in practice.

Studies have shown that the lack of real-world experimental data can adversely affect the performance of AI-based models, particularly in areas such as accident identification and control rod behavior [4]. Furthermore, the heterogeneity of dataset selection across lab studies has been pointed out as a potential issue. Algorithms may present different performances by inputting certain datasets and exhibiting the above two biases at different levels. A proposal for the development of unified nuclear datasets suitable for a certain domain has been made in order to create a better foundation for synchrotron radiation sources, and it certainly sounds interesting [4].

Furthermore, the incorrect belief that big data drawn from centuries of nuclear power production can be easily exploited to design such models is an example of cognitive bias. It is, in fact, an issue of both quality and quantity that creates the challenge of using data. For instance, normal samples dominate the rare fault samples in the case of fault detection. Consequently, this becomes the main source of multiclass classification problems with supervised ML models. Although data augmentation is a technique that can be used for the elimination of the issue, the fundamental need is for high-value, high-quality data that are really a mirror image of a working nuclear reactor [4].

These obstacles can be solved through a multidimensional approach that involves the involvement of various stakeholders, such as data-gathering objectives and activity plans, data curation, and data infrastructure design, as well as the development of tailored AI, which can be effectively deployed in the very specific cybersecurity constraint of nuclear reactors [4].

6.2. Black Box Dilemma: AI Invisible Hidden Layers

Another major concern regarding the use of AI in nuclear power plant research is the so-called "black box" nature of such models. The internal workings of DL architectures, with their hidden layers and complex feature encoding processes, are often opaque and difficult for humans to interpret. Although they have more complex mechanisms inside, models of greater performance also lose some of their explicability. However, models that code for rules can also have issues with that, i.e., they may not be able to eliminate the complexity of a nonlinear system, which is characteristic of nuclear reactors [4].

A good result would be an AI model that could combine the best effects with such clarity that the processes and criteria responsible for the model's outputs can be easily understood. Among other things, achieving performance and interpretability in the nuclear reactor domain will be the main success of future AI algorithms in the safety-critical domain of nuclear reactor design and operations [4]. Furthermore, it has been demonstrated in previous research that DL models can be heavily influenced by adversarial attacks, in which case minor distortions of the data input can later cause the model to make significant errors. The most serious issue that arises from the current situation is that AI systems have the nuclear energy domain as their main battlefield, where the safety and reliability of reactor operations are of paramount importance [4].

To solve these issues and, at the same time, enhance the promotion of a harmonious connection between AI and nuclear technologies, scientists have to give priority to the transparency, robustness, and accountability of AI models rather than focusing only on the accuracy metric. Making AI models that can not only achieve high performance but also have features of interpretability, reliability, and sufficiency against dangerous elements is necessary for the secure and effective employment of these modern computational tools in crucial nuclear reactor research and operations [4].

Furthermore, a challenge of interpretability could arise. AI models implemented in nuclear power plants are complex and can be difficult for operators to comprehend. Ensuring transparency in the decision-making processes of these AI systems and the hidden AI layers is crucial as operators need to understand and trust AI's judgment to effectively verify its behavior [2].

6.3. Cybersecurity Within Mobile Computing

The implementation of artificial intelligence (AI) and mobile computing in nuclear power plants introduces a significant challenge for cybersecurity, especially because the reactor data would be transmitted virtually across mobile devices, introducing significant cybersecurity challenges in the development of these technologies. For these reasons, a thorough understanding of the attacker's capacity and motivation is necessary to protect both wired and wireless digital instrumentation and control (I&C) data, systems, and networks from malicious intrusion. Attackers with varying motivations, capabilities, and resources, such as nation-states, disgruntled employees, or cyber-activists, can exploit system vulnerabilities through various techniques, including mimicking, man-in-the-middle attacks, network spoofing, packet sniffing and modification, sensor masking, and denial of service [42]. The complexity and sophistication of these attacks, particularly from advanced persistent threats like nation-states, pose a significant challenge to the secure development of AI and mobile computing systems. Vulnerabilities in these systems are not always intuitive, requiring specialized skills and tools for identification and remediation. Comprehensive threat analysis and security evaluation tools are necessary to properly assess risks and implement robust protection measures [42].

Emerging research has explored models and methods for vulnerability identification in critical systems, including nuclear power plants, which can provide insights applicable to the development of secure AI and mobile computing. These approaches, such as safety margin estimation, attack taxonomy classification, and event classification schemes, can help identify the most vulnerable components and prioritize security measures. Addressing the complex and evolving cybersecurity threats is crucial as AI and mobile computing become more deeply integrated into critical infrastructure and everyday applications [42].

6.4. Regulatory Compliance Challenges

The integration of AI and mobile computing in nuclear power plants necessitates modifications to existing regulations and the development of new guidelines. This is necessary to ensure compliance while preserving the highest standards of safety and reliability [2].

6.5. AI and Human Collaboration Challenges

The participation of AI and mobile computing in NPP involves a shift in human duties, moving from direct manual operation to supervisory and decision-support functions. Active collaboration between human operators and AI systems is vital to ensure safe and ideal plant operation [2].

6.6. Cost Challenges

Implementing AI technologies and mobile computing in NPPs comes with considerable costs, such as setup investment, workforce training, and continuing maintenance. Matching the benefits of these technologies with the accompanying expenses could be a challenge for NPP workers [2].

6.7. Training and Expertise Challenges

The nuclear industry needs trained and skilled personnel who can efficiently employ AI technologies and mobile computing. This can be achieved by attracting specialists from other industries and offering specialized training to current personnel in the nuclear field. Merging these experts with area knowledge from the energy sector is advised [2].

7. Mobile Computing and AI Features in NPP Future Application

The integration of artificial intelligence and mobile computing technologies holds significant potential for enhancing the safety, efficiency, and reliability of nuclear power plants. Figure 11 illustrates the potential areas of application of AI and mobile computing in the nuclear industry, based on the literature review in the present article. AI algorithms can serve as efficient data-processing mechanisms, enabling intrinsically safe operation and effective accident investigation. By leveraging AI and mobile computing, NPPs can improve their performance and move towards more environmentally friendly and cost-effective operations. Artificial intelligence algorithms allow for the autonomous construction and calibration of virtual representations of the NPP core, enabling advanced parameter identification, state estimation, and anomaly detection capabilities. Furthermore, the integration of AI and IoT can transform NPP control systems, facilitating enhanced communication, information sharing, and decision-making processes among stakeholders. Collaboration between nuclear experts, AI specialists, and regulatory bodies is crucial to ensure the effective and safe implementation of these cutting-edge technologies within the nuclear industry while maintaining the highest standards of operational safety. As the nuclear sector continues to digitize and accumulate vast amounts of operational data, the application of AI and mobile computing offers promising solutions to address the complex challenges faced by NPPs, ultimately contributing to their enhanced safety, efficiency, and long-term sustainability [2]. The integration of the advanced technologies of AI and mobile computing, when implemented thoughtfully and with a focus on safety, can revolutionize the nuclear industry, unlocking new possibilities for clean, reliable, and cost-effective energy production.

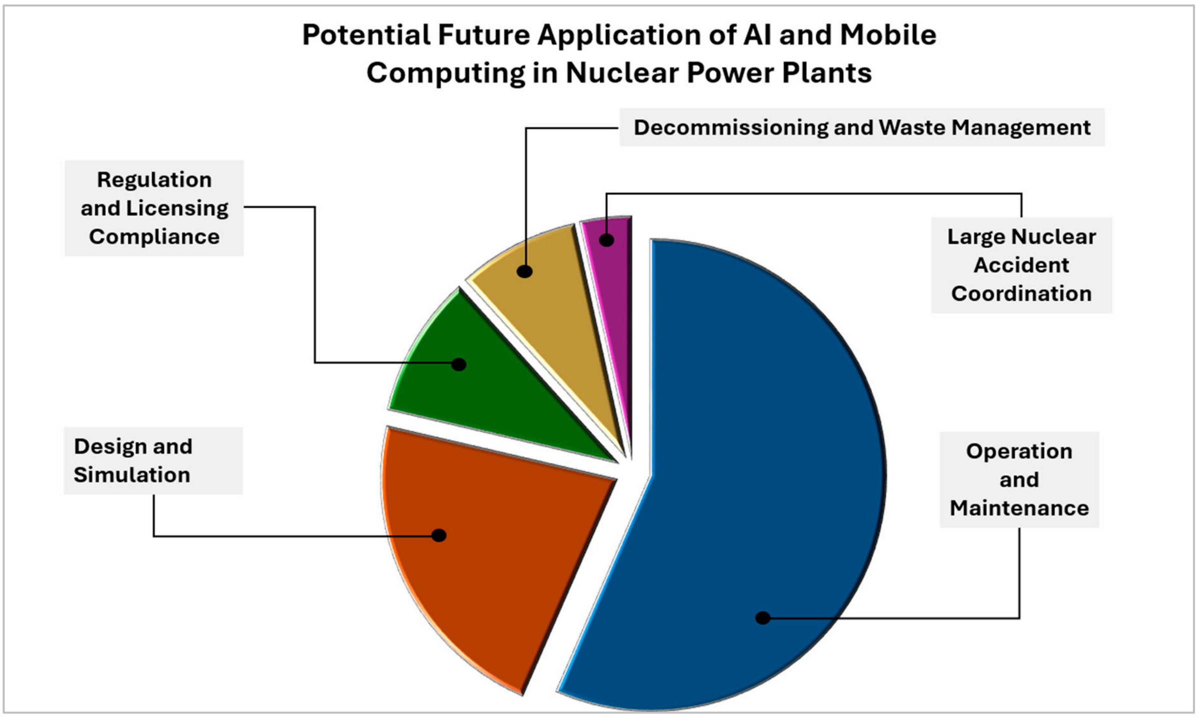

Figure 11. Potential future areas in NPPs for integrating AI and mobile computing.

8. Future Work Directions

The integration of AI and mobile computing in nuclear power plants (NPPs) is an evolving field with vast potential. Future work should focus on enhancing safety, efficiency, and reliability while addressing regulatory and security concerns. One key area is advanced predictive features in nuclear power plants, which involves improving AI algorithms for real-time data integration and anomaly detection to enable more accurate and proactive predictivity. Furthermore, AI-driven risk assessment coupled with mobile computing features for sending early warnings via mobile devices is a recommended area of research for future direction because it enhances overall plant safety and increases the reliability of nuclear power. Remote monitoring and inspection are also an important direction for future work recommendations in the field of AI and mobile computing because sending the nuclear power plant real-time data allows for autonomous inspection and continuous remote monitoring, which are very important for the safe operation of the plant. Therefore, we recommend focusing on AI-powered drones and robots, mobile control interfaces, and advanced image/sensor data analysis in future work in this evolving area. Additionally, AI and mobile computing integration to enhance decision making within nuclear power plants is another crucial recommended area of research in the coming years. This is because AI-based algorithms provide predictions of different case scenarios based on real-time data and historical data, which make it a powerful tool in the nuclear industry. Added to that, the features of mobile computing allow different stakeholders to be involved in decisions, which enhances the plant's response and, hence, safety. For those reasons, more research in this field is recommended to optimize the decision-making process in NPPs.

It is also highly recommended to include different parties during the application of AI and mobile computing, such as lawyers and legal authorities, because this is a novel field that needs new regulations and guidelines for sending nuclear power plant data to mobile devices in different locations. Hence, we recommend more research on assigning new regulatory compliance to meet the requirements of AI and mobile computing safety standards to ensure the safe use of nuclear material around the world. Lastly, the most important area that needs more research in the context of applying AI and mobile computing to the nuclear power plant is cybersecurity. This is a crucial feature for ensuring the continuity of real-time data transmission safety. However, this presents many challenges related to cyber-attacks and hackers. For those reasons, we recommend that sophisticated cybersecurity measures and new protocols be addressed in future work and research. Figure 12 represents the number of published papers over the period of 1985 to 2024. In compiling the data presented in this figure, a significant effort was made to estimate the number of published papers related to AI applications in the nuclear industry. Given the vast amount of literature available, we aimed to collect an approximate count, focusing on selecting the most important and influential papers from highly reliable academic websites and databases. The papers chosen were carefully filtered to ensure relevance to the topic and significant contribution to the field. From Figure 12, we can conclude that not much work has been conducted in the area of artificial intelligence in the nuclear power plant industry and there are significant gaps between 1989 and 2010. Therefore, we recommend more work on the overall topic of implementing artificial intelligence in nuclear power plants.

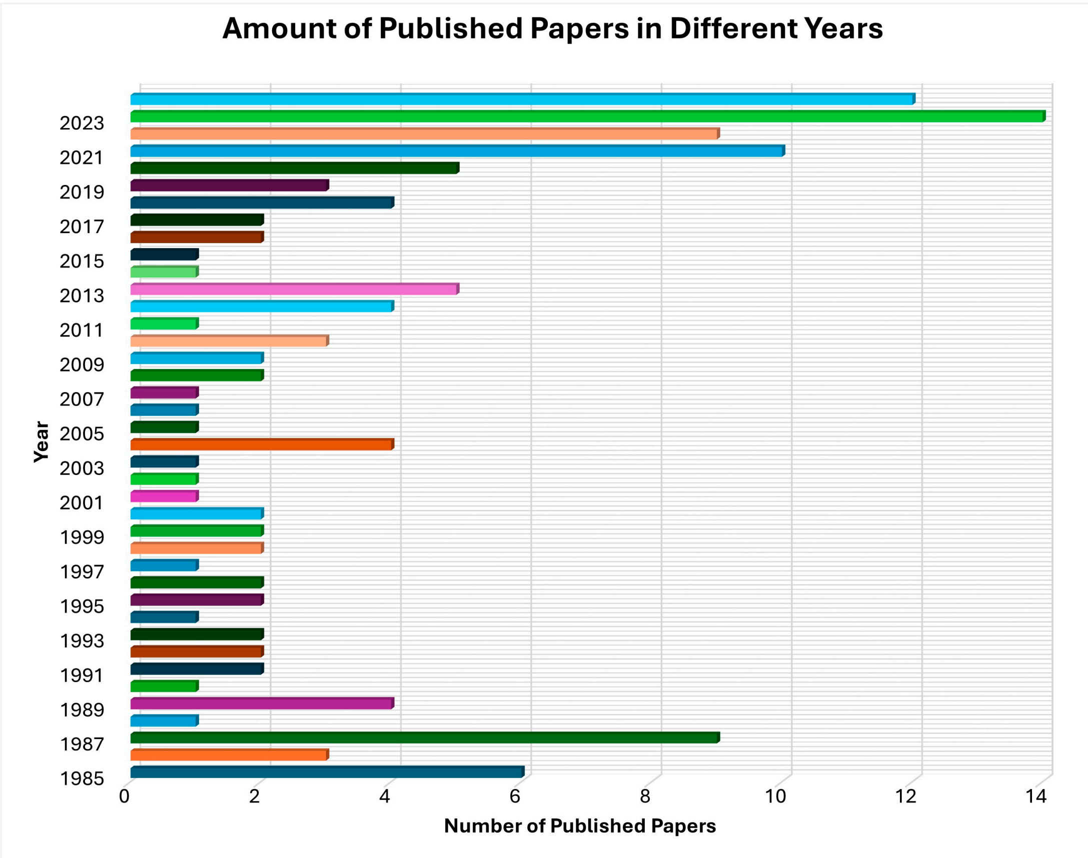

Figure 12. Number of published papers in different years.

Underlying all of these efforts should be initiatives to integrate data, enable advanced analytics, and foster cross-industry collaboration and continuous innovation. By prioritizing these future work recommendations, nuclear power plants can harness the full potential of AI and mobile computing to operate more safely, efficiently, and sustainably.

9. Conclusions

The integration of artificial intelligence and mobile computing in NPP systems is a transformative approach to optimizing the safety and reliability of nuclear power. The combination of the predictive capability of artificial intelligence algorithms and the real-time data transmission capability of mobile computing devices provides a promising area to enhance decision making in NPPs and provide continuous support for the safe operation of the overall plant. As technology continues to evolve, future developments in AI algorithms, IoT integration, and mobile interfaces will further enhance these capabilities, paving the way for even more robust and resilient nuclear power operations. However, the adoption of these technologies also necessitates addressing challenges related to cybersecurity, regulatory compliance, and workforce training. Ensuring the security of interconnected systems and maintaining compliance with stringent regulatory standards are paramount to realizing the full potential of AI and mobile computing in NPPs. In this article, we have reviewed the majority of scientific papers published in this field and proposed a novel idea for AI and mobile computing applications in NPPs. We have also addressed the challenges and features associated with this application, and various research directions were also proposed that would enable future researchers to propose better solutions for enhancing the safe use of AI and mobile computing in nuclear power plants.

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Abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
ML	Machine Learning
IoT	Internet of Things
NPP	Nuclear Power Plant
ANN	Artificial Neural Network
GA	Genetic Algorithm
DL	Deep Learning
EA	Evolutionary Algorithms
SVM	Support Vector Machine
PCA	Principal Component Analysis
LR	Linear Regression
RF	Random Forest
CNN	Convolutional Neural Network
RNN	Recurrent Neural Network
LSTM	Long Short-Term Memory
MTD	Mobile Terminal Data
RAND	Radio Access Network Data
PCND	Packet Core Network Data
SLA	Service Level Agreement
DL-based ROMs	Deep Learning-based Reduced Order Models
MACNOS	Modular and Adaptive Control for Networked Open Systems
PIMLAF	Physics-Informed Machine Learning Augmented Framework
BPNN	Backpropagation Neural Network

DNN	Deep Neural Network
ROM-ML	Reduced Order Modeling with Machine Learning
AAKR	Auto-Associative Kernel Regression
ANFIS	Adaptive Neuro-Fuzzy Inference System
BWR	Boiling Water Reactor
SMR	Small Modular Reactor
CRMS	Control Rod Position Measurement Sensor
LOCA	Loss of Coolant Accident
RV	Reactor Vessel
SG	Steam Generator
BOP	Balance of Plant
CA	Correlation Analysis
TRU	Transuranic Actinides
I&C	Instrumentation and Control

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