MSc Program
Environmental Technology & International Affairs

The Role of Artificial Intelligence and Emerging Technologies in Enhancing Safety in Nuclear Power Plants

A Master's Thesis submitted for the degree of
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supervised by
Dr. Kaluba Chitumbo

Maria Apolloner, BSc

11915515

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Vienna School of International Studies
École des Hautes Études Internationales de Vienne

Affidavit

I, **MARIA APOLLONER, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE ROLE OF ARTIFICIAL INTELLIGENCE AND EMERGING TECHNOLOGIES IN ENHANCING SAFETY IN NUCLEAR POWER PLANTS", 73 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

With the goal of enhancing safety of nuclear power plants, this study explores the potential of artificial intelligence integration within the field. While security and safeguards are equally important and the synergy between safety, security and safeguards will be discussed, the focus of the thesis will remain on safety. The research aims at demonstrating the advantages that developments in the field of artificial intelligence may have in enhancing safety that traditional methods do not possess. While the application of artificial intelligence systems within nuclear field is still hypothetical, the potential of the applications will be assessed. Using mainly literature review and first-hand insights from experts at the Joint Research Centre of the European Commission (Ispra, Italy), the thesis is a critical examination of the potential of artificial intelligence methods such as pattern recognition, simulations, autonomous and optimisation functions in enhancing key nuclear safety components. These encompass inter alia the design, the operations and maintenance as well as the monitoring of the nuclear power plant. Challenges and limitations such as ethical considerations or explainability are assessed and future recommendations and potential are explored. The key findings of the thesis are that the integration of artificial intelligence into nuclear power plants can enhance safety and efficiency, yet further research in various fields is necessary and real-life applications should be examined, to address limitations accordingly.

Table of Contents

List of Abbreviations

AI – Artificial Intelligence

ANN – Artificial Neural Network

EU – European Union

GW – Gigawatt

IAEA – International Atomic Energy Agency

IEA – International Energy Agency

JRC – Joint Research Centre (of the European Commission)

LLM – Large Language Model

ML – Machine Learning

NPP – Nuclear Power Plant

O&M – Operations and Maintenance

SMR – Small Modular Reactor

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1. Introduction

1.1 Context

Artificial intelligence (AI) is a transformative power in the modern world. It has demonstrated its disruptive potential across various industries and has great potential to positively affect the nuclear industry too. Taking into account challenges and limitations, this thesis will focus on presenting AI's impact in rendering nuclear power plants (NPPs) safer.

Seeing as a substantial share of the energy mix is supplied for by weather dependent energy sources, the shift away from fossil fuels raises the issue of providing the baseload needed to satisfy the demand, which is expected to particularly further increase due to sectors expansion of artificial intelligence and robotisation, that require constant electricity supply (Hjelmeland et al., 2025). AI is hence directly intertwined with the energy demand and might also serve in supporting the energy supply sector.

Nuclear energy plays an ever-more important role. According to the International Energy Agency (IEA, 2025), SMRs (small modular reactors) are likely starting to enter the market from 2030 onwards and will supply the needed base-load energy for data centres. Still, nuclear safety is a matter of concern for the public and from a political point of view. The safety of NPPs is dependent on the design, the safety features, the materials used and the operators running the plant. Accidents, although unlikely can still happen, therefore it is beneficial to look at how they can be prevented as well as better addressed through enhanced emergency response.

1.2 Problem Statement

An important hindrance to the deployment of nuclear power and its expansion, remains the challenge of providing safe nuclear power at a price that does not reduce the competitiveness of nuclear energy within the market (Rauch, 2023). Especially the perceived risk plays an important role, hence why the implementation of AI in the field of nuclear safety is promising and should be explored. The main costs of nuclear power plants are the ones connected to operational expenses (Nuclear Energy Institute, 2018). Maintenance and operation make up 60-70% of the operating costs of NPPs (Huang et al., 2023). It would therefore be beneficial to both increase safety and at the same time lower the costs of operation and maintenance (O&M). The goal of this thesis is not to analyse the competitiveness of nuclear power in the energy mix or to conduct a financial analysis but rather to show the tech-enabled safety enhancements which could be key factors for transforming nuclear into an even safer energy source.

Generally, AI is believed to make small and medium-sized enterprises of various industries more competitive (Cha, 2024), hence the hypothesis of AI doing the same for the nuclear industry. While the enhanced competitiveness through reduced O&M costs (Hassan et al., 2023) might be an ultimate end-goal, the thesis will mainly concentrate on the potential of AI rendering NPPs safer.

One of the main obstacles of nuclear energy adoption remains the public's distrust (Allison, 2012), hence increasing safety of nuclear power plants can aid in overcoming this barrier. Particularly in Europe, the opinions on nuclear vary greatly, with almost half being for and the other against nuclear energy (Aldave De Las Heras et al., 2024). Nuclear power has a great potential in becoming a preferred low-carbon energy source if it is rendered safer (Mari, 2014).

1.3 Importance of Safety

Ensuring safety during O&M of NPPs is crucial as any risk may have severe consequences. Examples such as Chernobyl, the Three Mile Island accident or Fukushima demonstrate the catastrophic outcomes when safety systems are insufficient or fail under stress (Ejigu et al., 2024). Fukushima's monitoring systems failed due to an outage (Jendoubi & Asad, 2024) hence AI could not have supported much either, without electricity. Nevertheless, Fukushimas's NPP Daiichi had monitoring systems which were not efficient, resulting in bad management and operational deficiencies already before the accident occurred (El-Sefy et al., 2021). AI could have been beneficial in the design process, for conducting a more adequate risk assessment for example.

Disasters like these substantially slow down the development of the nuclear energy industry and encourage the development of safer reactors (Hassan et al., 2023). In Chernobyl, the accident was also related to the inadequate safety culture, underscoring the importance of "*inherently safe reactors*" (Forsberg & Weinberg, 1990). Important safety measures were neglected, the design of the NPP being one of the factors and the human error being another (International Nuclear Safety Advisory Group, 1993). All of the above demonstrate how safety was an issue and the immense effects that the small shortcomings had worldwide.

The Nuclear power plant, as a system-of-systems is designed by the "*single-failure criterion*", which ensures that a failure of one element does not lead to a failure of other systems (Jendoubi & Asad, 2024). Even so, a minor malfunction in one of the systems bears the risk of expanding to become an issue for the whole plant (El-Sefy et al., 2021). While major accidents rarely happen, resilient safety measures are implemented to minimise risks, protect the environment and maintain public confidence in nuclear energy. The public is protected through various systems, that contain radioactivity, control the reactor and shut it down fast, also after shutdown, cooling is necessary and needs to be ensured (Hanks, 2013). During accidents, radioactivity may escape into the environment, which could lead to drastic health issues (Hassan et al., 2023).

Traditional systems and human supervision may not be enough for such high-risk environments like the nuclear energy sector. AI has been on the rise particularly in the past years and holds promising characteristics for replacing human skills and even augment human capabilities. Current research on AI explores areas like predictive maintenance, anomaly detection, decision-making support and various others which have great potential in enhancing safety of NPPs.

1.4 Objective

The aim of this research is to evaluate AI advances and opportunities within the nuclear industry, to render NPPs safe and secure, "*clean and reputable, inexpensive, workable, and well-grounded*" (Hassan et al., 2023). The thesis explores a way forward in applications of AI technologies within the nuclear sector, which to date are still very limited and rather hypothetical.

With the goal of enhancing viability of nuclear energy by rendering it safer, this thesis will focus on technological advancements and on how these emerging technologies in the sector of artificial intelligence can improve nuclear power plants through safety enhancements.

The future of nuclear energy is heavily dependent on the guarantee of safe and secure operation. A quote mentioned in the article by Ahearne (2010), underlines that "*a nuclear accident somewhere is a nuclear accident everywhere*", this can be seen through the impact that the Three Mile Island and the Chernobyl accident had on nuclear growth (Ahearne, 2010). Thus, if nuclear safety can be improved through AI, it is crucial to examine and assess its potential.

1.5 Significance of Study

This study bridges the gap between two very important topics. Nuclear power has been and will remain an important component of the global energy transition in reducing carbon emissions. Relating it to AI, which is continuously being applied to various industries in order to enhance safety and increase efficiency across its operations, underscores the importance in the context of nuclear energy, where safety is paramount due to it being a high-risk sector. While still at an early stage, and rarely being implemented in real life so far, the AI application within the nuclear sector will be of importance in the future.

This thesis will contain relevant research for policymakers, for future regulations as well as for experts in both industries, AI and nuclear energy. NPPs become more and more digitised and are very data-driven, hence the integration of AI is not only appropriate but strategically aligned with the industry's current and future developments. The focus on enhancing safety rather than other aspects of the NPP is due to the fundamental need of sustaining a strong safety in the plants, as this is one of the main limiting factors for nuclear deployment.

1.6 Personal Motivation

Studying Environmental Technology and International Affairs has shaped my interest in understanding hybrid risks and interdisciplinary challenges. As infrastructure becomes more and more digitalised, it is important to continue to ensure safe and resilient services. Energy disruptions due to environmental or other risks are becoming a threat for our society. As technology and AI become ever more embedded in our society and our reliance on them continues to grow, it is essential to ensure that it is safe and secure.

This thesis is motivated by my personal interest in the intersection of technology, the energy transition and international cooperation from a global perspective. While expertise knowledge and research in small specific fields are important and necessary, so is the understanding of the nature of the interconnected dimensions, to be able to address any current or future challenges accordingly.

2. Literature Study & State of the Art

In the following part the research question will be presented and the goal of this thesis, as well as relevant research in the field.

In an attempt to answer the topics mentioned, the research question for this thesis is formulated as such:

How can artificial intelligence enhance the safety of nuclear power plants?

To answer this research question effectively, some sub-topics have been defined:

- AI development
- Technological developments within the nuclear domain
- Technologies developed for safeguards, applicable for safety
- AI applications for nuclear safety
- Other advantages of enhanced nuclear safety

Safety with respect to NPPs is defined as "*the achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences*" (Hanks, 2013) in order to protect humans and the environment. Security is defined as the "*prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material*" (Hanks, 2013). Safeguards on the other hand ensures '*that nuclear facilities are not misused and nuclear material is not diverted from peaceful uses*' (IAEA, 2016b). The primary focus of this thesis will be on nuclear safety.

The objective of the thesis will be to critically assess the potential of AI in enhancing nuclear safety. While there is fragmented and specific research on AI applications in various subfields such as monitoring or predictive maintenance, there is no comprehensive study of AI enhancing nuclear safety from a holistic point of view. Analysing the potential of different applications, taking into account interdisciplinary challenges or future implications and evaluating them is crucial in this field.

The advantages of nuclear energy are laid out in the European Commission's Communication as decreasing the emissions of CO2 in the EU and as having relatively stable prices, but it is still advised to make efforts to reduce the costs of this energy source for future reactors. (An Energy Policy for Europe (SEC(2007) 12), 2007)

The base-load energy supplied for by reactors is cheap and new Gen IV reactors are thought to be even more sustainable and effective. While the cost estimates may vary greatly, digital automated control and improved technologies can both drive down the operating costs significantly and AI could also improve passive safety features. (Ahearne, 2010)

Nuclear energy is more reliable and less vulnerable to political instabilities, than renewable energies, however, there remains high uncertainty related to the deployment of nuclear energy, mainly associated with the safety of nuclear power plants (Ahearne, 2010).

It can be held, that while nuclear power reactors seem to be one of the safest and most reliable carbon-free energy sources, the social's perception and the cost that comes with it are the biggest hurdle, especially in Europe, where past disasters have had a lasting effect. Nuclear is as expensive due to the overstatement of the real risk and hence hindering or slowing down the fight against climate change. (Allison, 2012)

While many countries want to deploy nuclear power in the future, their main challenge remain the costs and keeping the operation of the plant safe. Costs, which are the main factor affecting competitiveness are closely related to safety. With the purpose of making nuclear energy more competitive in terms of costs, it is essential to get rid of the so called 'risk premium' as the MIT's report argues, as cited by Ahearne (2010). Accordingly, this risk is intertwined with safety, the public's perception and the regulatory uncertainty that comes with it. (Ahearne, 2010)

Allison (2012) argues that nuclear energy is already safe, "*radiation is dangerous only in the immediate vicinity of a nuclear detonation*", but that the main issue is the public's opinion. As an example, the author mentions the Fukushima incident where there was no fatality or grave hospitalisation related to it. The safety level for non-medical nuclear radiation is set very low with the goal of reducing public concern, whereas scientifically speaking, these levels could be "*1000 tines higher*" without causing any harm (Allison, 2012).

In particular, individuals with strong environmental values seem to support nuclear energy rather less, likely due to safety concerns. These concerns are at the core of what hinders the full-scale deployment of nuclear power. However, nuclear seems to be the key to reaching the goals set by policy and increase independence from imports of fossil fuels. (Bohdanowicz et al., 2025)

It is important to note that radioactivity does not propagate and multiply but can only be reduced with the passing of time (Allison, 2012). Taking this into account, would mean that sufficient containment and improved safety should suffice to prevent the spread of radioactivity. Allison (2012) argues that the AHARS (As high as relatively safe) approach should be chosen and applied rather than the ALARA (As low as reasonably achievable) as this entails much higher costs.

Not only could AI support operators in improving the safety and performance of a nuclear reactor (Albert, 2024), but it is also thought to improve the reliability (Wiles, 2019) and the efficiency. This is crucial when nuclear energy is highly debated in political discussions, as mentioned earlier. The infusion of AI increases safety, while at the same time bringing down costs (Argonne National Laboratory, n.d.).

AI seems to help overcome various challenges that have existed over decades. Methods like predictive accuracy, the detection of radiation or the recognition of patterns supports research and may support O&M of NPPs (Arhouni et al., 2025). Arhouni et al (2025) mention Fantoni and Mazzola's (1996) project in which its process signal validation (PSV) model can identify wrong measurements successfully through pattern recognition for example. Gomez Fernandez et al. (2017) also highlight this project in their paper, mentioning Fantoni and Mazzola's '*Computerized Accident Management System*" which can be used as a supporting tool by operators during accidents. These are only some of various examples showcasing the potential of AI in the nuclear safety sector.

The hypothesis of this thesis will be the following:

‘The study assumes that, when appropriately integrated, artificial intelligence systems can enhance the safety of nuclear power plants in ways that exceed the capabilities of conventional mechanisms.’

3. Methodology & Research Design

With the aim of effectively conducting research on this topic a qualitative analytical approach was chosen. The majority of the information was drawn from literature reviews of papers mainly from researchers, academia and official institutions. It also includes some legal and technical information, but this will remain limited. An analysis of the technologies within the sector of nuclear energy, more specifically nuclear safety, is conducted. The opportunities and challenges are critically analysed and discussed.

Further, a one-week visit to the European Commission's Joint Research Centre (JRC) in Ispra (Italy) was part of the research process. At the JRC, at the department 'Nuclear Data, Safeguards and Security' a substantive amount of information was gathered regarding nuclear safeguards. The results from this insight will also be included, by showcasing the possibility and proposing the implementation of safeguards technologies within nuclear operations processes and with the aim of enhancing safety.

While the focus of this thesis will be on nuclear safety during O&M, it is crucial to look at the advancements and solutions in other domains and explore the possibilities and potential of application within the field of interest. The JRC, which was created under the EURATOM treaty ((2016/C 203/01), 2016), works closely with the IAEA and ensures nuclear safety across Europe, by conducting research in the nuclear field (Maiani et al., 2018). In ensuring the 3S (safety, security and safeguards) the JRC supports the peaceful use of nuclear technology on European level while the IAEA does this on a global level (Maiani et al., 2018).

Nuclear safeguards are an important topic in international relations as non-proliferation is a matter of concern for all countries. Although safety and security of NPPs can also have an impact internationally, they fall under national legislation and authority (IAEA, 2019). Nevertheless, the synergy of the 3S (safety, security and safeguards) should and will be taken into account, in order to advance developments in all three respective categories. (Maiani et al., 2018)

The focus will be on the safety of nuclear power plants, mainly during O&M, taking into account the technological developments from the JRC in the field of nuclear safeguards and blending in the acquired knowledge. As the JRC's mission is to provide science for policy regarding nuclear safeguards for the EU, it is conducting research and developing technologies for the purpose of non-proliferation and does not focus on developing security- or safety-improving technologies, as mentioned before, these fall within the competence of the state's national legislation (IAEA, 2019), hence the international efforts in enhancing safety remain rather limited. The approach chosen in this regard is to explore the potential of safeguards technology advancements' application for safety purposes within a plant's O&M.

The goal of the thesis is to comprehend the complexities regarding O&M of NPPs and analyse the potential of AI advancements, which assist in making nuclear a more viable energy choice, by enhancing its safety. The thesis will propose new frameworks that might be missing or recommend research in specific fields. It will further connect safeguards to safety, demonstrating the interdisciplinary opportunities. In aiming at making sense of the literature, the thesis will critically examine the research and identify gaps as well as emerging potential.

The research question will be, as mentioned before, the following:

How can artificial intelligence enhance the safety of nuclear power plants?

4. Research Chapters

4.1 The Potential of Artificial Intelligence and Related Technological Advancements

In this part, Artificial Intelligence applications will be examined and their potential application within nuclear safety will be covered. In Figure 1 an overview of the various forms of AI can be seen. Although not all aspects included in the illustration will be thoroughly discussed, this figure shall serve for better understanding.

For simplification, Figure 1 shall support the conceptual understanding of the following part, which will dive into the explanation of AI systems. The potential of various of them in enhancing the safety of NPPs will be examined.

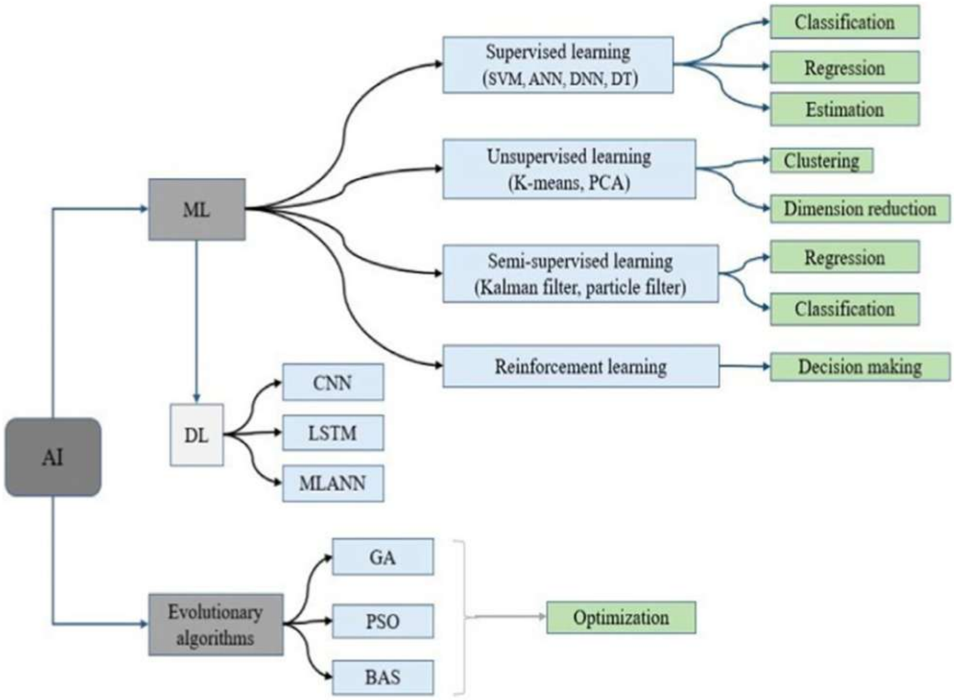

Figure 1: Framework of AI algorithms and their applications (Barja-Martinez et al., 2021; Bhat et al., 2023; Huang et al., 2023; as cited by Ejigu et al., 2024)

The abbreviations will now be briefly explained, before further elaborating on the subfields. The main subset of Artificial Intelligence (AI) are Evolutionary Algorithms and Machine Learning (ML), which also includes Deep Learning (DL). Evolutionary Algorithms such as the genetic algorithm (GA), the Particle-Swarm Optimisation and the Beetle Antennae Search (BAS) are used for optimisation purposes. DL as a subset of ML includes Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTM) and Multilayer Artificial Neural Network (MLANN) systems. ML is subdivided into various forms of learning, which will be further elaborated later on. These learning processes are mainly used for classification, clustering, regression and dimension reduction but also for estimation and decision-making

The recent boom of artificial intelligence has brought about important transformations and made 'AI' a commonly used term in our daily lives. This broadly applied term encompasses various types of computer systems, which solve issues by imitating biological processes, natural to human or animal brains, such as learning or problem-solving (Mata et al., 2018). Artificial Intelligence has disrupted our society by being an innovative solution to optimisation problems in the industry (Aldoseri et al., 2024).

The digital transformation has brought about a significant increase in big data. Traditional methods struggle to 'keep up' and effectively 'deal' with such big amounts of data (Aldoseri et al., 2024). Big data is defined by its great volume, variety and velocity (O'Leary, 2013). In recent years an increase of those three can be noticed and makes analysis of data more and more complex. Being able to make use of big data constitutes a paradigm shift from intuitive decision-making to decisions that are data-based (O'Leary, 2013).

AI allows for making use of big data and increase the effectiveness at which data is being analysed, by leveraging its pattern recognition abilities. Sources of big data may be sensors or various types of machines, present in nuclear reactor, inter alia. Hence why it would be recommendable to employ AI for tasks making use of big data.

In Figure 2 various areas can be seen, which make use of big data and could help enhance areas such as nuclear safety. All of the listed elements are important areas of NPP management. Seeing as these areas are based on big data, AI has a lot of potential in enhancing these areas.

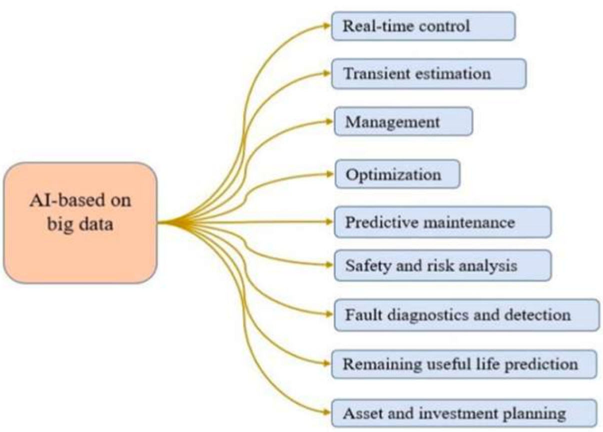

Figure 2: Application of AI algorithm and big data computing (Shukla et al., 2019; Yüksel et al., 2023; as cited by Ejigu et al., 2024)

AI has revolutionised various industries in their operation processes and has impacted competition. This continuously evolving technology helps companies innovate and optimise their processes, to gain a competitive advantage. By perceiving its environment AI 'reacts' based on what maximises its chance to attain a specific goal (Ongsulee, 2017). AI is able to divide problems into easier subtasks to facilitate the attainment of the overall defined goal in reducing errors and enhancing efficiency (Cha, 2024).

When talking about AI from a broader perspective, a characteristic of AI is its ability of mimicking human logic for making decisions, through the reception and analysis of inputs and production of a respective output (Arhouni et al., 2025).

The goal in this regard would be to make nuclear safety systems sufficiently autonomous to be capable of assessing new signals without the need for specific training for new input. This could significantly affect safety of O&M as it could reduce human errors.

Technologies that exhibit human-like intelligence characteristics are classified as AI. Some of these characteristics may include natural language processing, perception and reasoning to solve nonlinear complex problems. Machine learning (ML) is a category of AI that works in that way, generating its own logic from the input data (Arhouni et al., 2025). As a subfield of AI, machine learning (ML), gives "*computers the ability to learn without being explicitly programmed*" (Ongsulee, 2017) or following a fixed set of instructions given by the programmer or an operator. Instead, the system can improve its performance independently.

4.1.1 Machine Learning

Through the automatic analysis of data, ML collects information based off which, it is possible to classify or predict unknown data (Huang et al., 2023). The four categories of ML are reinforcement, supervised, semi-supervised and unsupervised learning (Ejigu et. al, 2024). In an unsupervised learning setting, the system is provided with unlabelled data, not knowing what the correct output is and with the task of identifying a certain pattern itself (Arhouni et al., 2025). Supervised learning is used to categorise data, with neural networks as one of the most common examples of supervised learning (Hassan et al., 2023). Reinforcement learning is a method in which a machine learns through trial and error, basing its decisions on the goal to maximise rewards (Huang et al., 2023).

Supervised and unsupervised learning are the most common implemented ML methods, with around 7 out of 10 ML systems being supervised. By using labelled input and the known output, the algorithms of supervised learning are trained. ML originated from pattern recognition studies and creates its own model based on input data. In the case of supervised learning, classification or regression for example, ML uses patterns to predict new incoming data and its corresponding values. Unsupervised learning on the other hand is not provided with any labelled historical data. As mentioned earlier, ML must identify a pattern independently. (Ongsulee, 2017)

Machine Learning is a central research topic in regard to autonomous control systems (Hassan et al., 2023). It has demonstrated its viability in autonomisation of various machines, while still rarely used within the nuclear domain (Gomez Fernandez et al., 2017), it is a research area of interest which should be further explored. ML can also provide significant support in "*early accident diagnosis*" where any major problem is avoided by identifying potential anomalies or other concerns (Arhouni et al., 2025). In nuclear safety, an early diagnosis of an accident is crucial for preventing further damage. By offering early insights the AI could support operators in responding in a timely manner to minimise further escalation of the situation. One of the major problems after the Fukushima Daiichi accident was the delayed action and poor situational awareness (BBC News, 2011).

At various accidents, the delayed response was a major problem. AI could have calculated and responded much quicker. Whether it was at Chernobyl or at Fukushima, AI could have supported where humans made a mistake or overlooked crucial parts. The unsafe test procedures at Chernobyl might have been prevented. All of this is hypothetical and there is no proof that AI could have prevented the disasters but there is substantive evidence showing the potential AI has in supporting operations and enhancing safety, particularly in emergency responses.

4.1.2 Deep Learning

Deep learning (DL) is a subset of ML, that uses multiple nonlinear layers to learn by performing classification and identifying patterns in data. Artificial neural networks (ANNs) are one of the most efficient DL methods. Convolutional Neural Networks (CNNs) are one type of feed-forward ANNs and are commonly used in computer vision for image or video classification or for detection of objects. (Ongsulee, 2017)

4.1.3 Artificial Neural Networks

ANNs are computational models based on the functioning of the human brain. They are able to learn from observing data by including various layers in their structure. The synaptic structure of these neural network systems allows for them to learn tasks just like humans and recognise patterns without having to be programmed on a specific task. ANNs can accurately predict system's behaviours, which can support decision-making processes that require quick analysis, hence also nuclear operations. (Gomez Fernandez et al., 2017)

The autonomous pattern recognition of AI is the basis of data-driven models (DDMs), different from traditional models, they do not rely on physical laws and equations and hence require less computational resources. DDMs 'learn from data' by comparing inputs and outputs and identifying a dependence through optimisation, by reducing the variance between real and estimated values. ANNs can be used to simulate data that will be used by DDMs. (El-Sefy et al., 2021)

Particularly in the nuclear domain, where acquiring real-life data can be risky, difficult and costly, ANNs can be employed to simulate NPP behaviour under various conditions. In Chernobyl for example, using AI for simulation processes could have been safer rather than conducting risk tests.

Abuzaid (2024) emphasizes AI's "*ability to augment human capabilities*" and increase competitiveness of companies and industries. Decision-making based on digital data is heavily reliant on automated processing (Araujo et al., 2020). When AI is responsible to take decisions, its decision is often classified as equal and sometimes as even better than those taken by experts in the field (Araujo et al., 2020), this offers great opportunity for AI applications in several industries, including the nuclear industry.

4.1.4 Graphics Processing Unit

AI functioning is based on probability and optimisation method. A driving force in the field of AI has been the recent development in GPUs (graphics processing units). While they are not an AI algorithm, they are an important factor in the adoption of AI. GPUs are electronic circuits which can accelerate AI tasks, as they can process tasks simultaneously due to their higher computational power. GPUs are useful for training deep learning. (Ongsulee, 2017).

This is very relevant for nuclear safety as the GPU's parallel processing of data from different compartments can be crucial in operation processes for real-time monitoring of sensors for example. Humans do not possess multitasking capabilities at such an advanced level.

4.1.5 Internet of Things

Alongside big data, the Internet of Things (IoT) is also closely connected to AI. This cutting-edge technology together with AI marks the 4^{th} industrial revolution. The IoT refers to a network of physical devices and supports intrasystem communication (from machine to machine) as well as facilitating the communication between the systems and humans. The IoT as well as AI, are believed to improve businesses and maximise their profits through real-time analysis and operations enhancement through optimisation. The disruptive nature of these technologies is commonly viewed as positive. (Păvăloaia & Necula, 2023)

The connection of the physical world to the digital world enables smarter faster and ultimately safer plant operations. The facilitated intercommunication can also contribute to increased safety at nuclear plants. Integrating and connecting data from different operational processes and supporting their understanding is crucial for O&M management. AI together with the IoT can provide operators with a holistic overview of the whole plant and assist their decision-making.

The support of decision-making processes by AI systems is useful for safety and command and control in various fields. Augmentation of human capabilities, as mentioned earlier can be achieved by making AI systems "*reason, learn, remember, plan and analyze*". AI is specifically useful in analysing unstructured big datasets. The AI decision-making support tools use input, processing and output sequentially, with feedback loops. (Phillips-Wren, 2012)

AI's most promising abilities are prediction, preventive maintenance, and risk management in various sectors (Zong & Guan, 2024). In the following table, the AI's potential and its impact within the nuclear domain will be explored.

To summarise the identified potential, a table has been created, showcasing which AI systems could be leveraged, where in the nuclear sector and for what purpose:

Table 1: Overview of AI applications and their potential (own work)

AI tool & other technologies	Area of Application	Function	Potential	Enhances
Machine Learning	Operations & Monitoring, thermal hydraulics, anomaly detection	Learn from historical data & predict	Optimise processes and support data-based decisions	Safety
Deep Learning	Image analysis, verification of nuclear fuel assemblies, core monitoring, fault diagnosis	Extract relevant information from big data from sensors	Make sense of vast amounts of data of NPPs	
Artificial Neural Networks	Risk mitigation, Decision-making	Make sense of complex nonlinear relationships	Reduce human error	
Graphics Processing Unit	Image processing, surveillance	Identify anomalies	Increase efficiency & speed of anomaly detection	
IoT & smart devices	Operations & Monitoring, Maintenance	Provide real-time data	Reduce human exposure to radiation	

Table 1 serves to showcase and summarise possible applications of the aforementioned technologies within the field of nuclear energy. The ultimate goal is to enhance safety, and all systems are thought to be capable of doing so, as can be seen from the table. Nevertheless, the potential of AI can vary in its form and area of application. Deep Learning as part of Machine Learning supports the operator's decision-making by making sense of big data. The Artificial Neural Networks could replace human efforts and reduce their errors through reasoning. The IoT might enhance safety by reducing human exposure to high-risk zones, through improved human-system communication and autonomisation of processes and the Graphics Processing Unit can support through *enhancing image processing for monitoring practices, this could help prevent any major emergencies through early warning.*

4.2 Synergies (3S)

4.2.1 The Importance of Synergies

While this thesis is about enhancing safety of NPPs, it is important to address the synergy of safety, security and safeguards. Particularly for regulatory purposes, a holistic approach is essential to effectively address any risks or problems, seeing as the three areas are closely intertwined. The necessity of a cooperative harmonised regulatory framework addressing the 3S was underlined at a high-level meeting of the IAEA (Iturria & Li, 2022).

There is a strong interconnectedness between safety, security and safeguards, making up the so-called '3S' concept (Hanks, 2013). The 3S approach aims at discussing the three simultaneously. All three have the goal to protect people and the environment (International Nuclear Safety Group, 2010), hence they overlap in various aspects. Consequently, many efforts in enhancing one, result in the improvement of the other too. Synergies between security and safety include passive systems and barriers which serve the purpose of both (International Nuclear Safety Group, 2010).

Though, it is important to note that the opposite may be equally true. "*Design features that are introduced to serve safety purposes can at times be antagonistic to the achievement of security purposes, and vice versa*" (International Nuclear Safety Group, 2010). The International Nuclear Safety Group (2010) mentions the implementation of security barriers equally hindering quick access for operators, in case of a safety emergency. An important example in regard to AI and safety on the other hand could be the hypothetical implementation of digital AI systems for safety purposes, resulting in new points of attack for cyber attackers, which leads to poorer security.

The 3S approach is crucial in various stages of the nuclear sector, starting with the design phase. Containment design is crucial for all three areas and close relationships such as these should be taken into consideration. Nevertheless, "*over-designing one element*" could potentially have negative effects on another. (Hanks, 2013)

The design phase is particularly important in regard to safety, as all design decisions will have an impact on later O&M, whether it is the material chosen, the equipment or the integrated safety systems. (IAEA, 2016a)

National regulatory frameworks exist to address safety and security issues, hence providing design guidelines which must be met by NPPs. Not only during the design phase, but throughout the lifetime of an NPP, the risks must be continuously assessed, to accordingly address them. (International Nuclear Safety Group, 2010)

The challenge in this regard is that while systems applications may be updated and various sub-parts me be replaced while NPPs are in operation, the choices taken during the design phase can hardly be altered later on. This may be problematic, as technological advances and breakthrough can occur at any moment, and what might be the most edge-cutting solution today could be considered outdated tomorrow.

In particular, the close relationship of safety and security is highlighted in existing research, but it is equally important to explore the synergies with nuclear safeguards. While maybe not as evident, the synergy between safety and safeguards bears a lot of potential. The safeguards technologies encountered at the JRC of the EC will be evaluated from a nuclear safety perspective and the potential applicability will be analysed, which has not yet been done before.

Consensus exists on the belief that the 3S shall serve as a foundation for deploying new nuclear power plants (Oku, 2020). While harmonisation of the 3S is crucial as the 3S approach may support the connected strengthening of each field, it is certainly still important to assess each of them on an individual basis to ensure their purposes successfully and avoid any oversight.

4.2.2 AI Advancements in Safeguards Technologies (JRC) for Safety Applications

As part of the assessment, a research visit was scheduled, to explore the potential of AI advancements in other areas and evaluating the possible cross-sectoral applications. The visit took place at the JRC (Joint Research Centre) of the European Commission, which has one of its seats in Ispra, Italy. The research visit at the Unit ‘Digital Systems for Safeguards and Non-proliferation’ within the ‘Directorate for Nuclear Safety and Security’ lasted for a week, dating March 31st - April 4th 2025. During the visit, interviews with various experts, helped in guiding the research and in gathering information and documents relevant for the thesis. Some of the newest technologies which will be discussed now, were also available for demonstration purposes.

The JRC in Italy focuses on safeguarding technologies, nevertheless these technologies could be potentially applied within NPPs during O&M processes for safety purposes. The JRC Ispra focuses on non-destructive examination (NDE) methods for nuclear safeguards and containment, by developing advanced digital technologies. In this regard, the application of AI within the field of NDE (Aldave De Las Heras et al., 2024) will be explored. The potential applicability of these technologies for safety purposes will be analysed and evaluated.

The safeguards technologies the JRC is enhancing through AI are the following: Mobile Laser Scanner Platform (MLSP), Laser Curtain for Containment and Tracking (LCCT), Robust Indoor Localisation in complex scenarios (RISE), 3D surveillance and Passive Gamma Emission Tomography (PGET).

The deep learning approach, used for Passive Gamma Emission Tomography (PGET) (Sanchez-Belenguer et al., 2020), seems to show limited potential use in O&M practices. Nevertheless, as PGET is used for verifying the contents of nuclear fuel assemblies, it may very well be employed to confirm no radiation is present during human handling of critical material. The advantage of PGET is that it is a non-invasive visualisation tool which measures the emitted gamma radiation without needing to open the fuel. *It could also be used to localise any radiation areas, to support in the planning of safe work environments and monitor the structural integrity. Enhancing the PGET data through DL can significantly speed up simulation processes.*

Video surveillance is actively employed for nuclear safeguards but is also present at NPP facilities mainly for security purposes. Including machine learning in the computer vision tasks like detecting objects, summarising or classifying videos can be beneficial. At the

JRC an interactive deep model has been trained for retrieving video frames from surveillance footage. In this case, feature extraction is employed, through pattern recognition from image data. Regions of interest (ROIs) are selected in which the system must identify the presence or absence of a defined object. (Casado-Coscolla et al., n.d.)

Neural network developments and deep learning have had an enormous impact on the functioning of computer vision too. Traditionally, the most time-consuming task was the algorithm creation. With the recent progress, deep learning models can now be trained with image data. Video surveillance plays a key role at any industrial site but particularly at NPPs, where safety and security are both of critical importance. While in modern times, cyber-attacks have become more and more present, ensuring physical protection is equally as important. Employing change detection algorithms, can considerably reduce the workload. Important to note though, is the possible increased number of false alarms, due to differing light conditions. (Wolfart et al., n.d.)

In terms of safety, this method could be used for monitoring critical operations and identifying safety-critical events or any faults, to suggest corrective maintenance or alert in case of emergency.

Cameras constitute an important part of monitoring and surveillance at NPPs, mainly for safeguards reasons rather than for safety. Nevertheless, the active learning framework tool (Casado-Coscolla a et al., 2024) introduced by the JRC and employed for video reviews can be used for safety reasons too. This method could support the fault alert through visual analysis and detection of anomalies.

While cameras are more cost-efficient than lasers, lasers have experienced substantive growth over the past years. Lasers are "*more robust*", "*deliver consistent depth information*" and its "*background subtraction operations are simpler*" (Casado-Coscolla et al. b, 2024). Deep learning has revolutionised the 3D object recognition, by using an "*automatic data-mining technique*" instead of having to manually design the methods. The JRC's hybrid approach to bridge 2D and 3D by using deep learning, can substantially reduce the costs and computing efforts that would normally be needed for 3D object recognition models. The advantage of lasers in comparison is their functioning even at poor visibility. (Casado-Coscolla b et al., 2024)

This technology could be employed at NPPs in O&M for monitoring and human or object detection, even in difficult-to-reach zones or where radiation is high.

The LCCT (laser curtain for containment and tracking) is also considered to be more reliable than cameras in detecting events, due to higher precision. LCCT is already used in various NPPs for surveillance purposes of nuclear material. Combining cameras with LCCTs can increase the surveillance effectiveness. This certainly produces a lot of data output, hence why efforts exist to improve LCCTs by employing AI techniques. (European Commission, 2023)

Operators also need to carry out inspection tasks during O&M for safety which are not related to safeguards. The aid of an LCCT technology with a camera can support the operator's tasks in providing real-time data, which could then be analysed by an AI tool.

Another technology developed at the JRC for safeguarding inspections is the so-called 'Robust Indoor Localisation in Complex Scenarios' (RISE). This portable 3D LiDAR sensor integrated together with a spherical camera maps indoor environments without the need for labelling by humans, but by using AI. This technology does not require GPS and can use 2D images for inference, making it more cost-efficient. RISE can provide guidance and alert and support the inspector in real-time. (Sanchez-Belenguer et al., 2020)

The deployment of mobile robots, equipped with AI, which have the ability to match indoor images to their location, could enable automated inspection tasks in high radiation zones, protecting the workers and reducing their exposure to radiation.

As demonstrated, various safeguards technologies could be employed to enhance safety at NPPs during O&M. The majority being used for maintenance, inspection and detection, while protecting operators, reducing their exposure to harmful radiation and ensuring the safety and integrity of the plant. It would be recommendable to focus future international research on such technologies with the purpose of also enhancing safety during operation. International collaboration in academia as it exists for safeguards, drives innovation and has shown great developments. A more integrated international *framework to cover all 3S rather than mainly emphasising safeguards is needed. Safety, security and safeguards are increasingly intertwined and need a holistic approach that encourages developments in each field and simultaneously drives improvements in the other fields.*

As demonstrated, various safeguard technologies may be applied to safety areas. The synergy and the integration of the 3S is crucial in exploring possible developments in any of the areas. Seeing as safeguards is widely discussed, and international efforts in this field exist, developments in safeguarding technologies are advanced and continue to advance. It would be beneficial to expand international efforts on safety and security issues too and enhance cooperation.

The application of safeguard technologies for safety purposes has not yet been explored but this research shall support the further exploration of these intertwined domains.

4.3 Technological Developments in the Nuclear Domain related to Safety

To effectively analyse and assess the potential of AI in enhancing the safety of NPPs, it is paramount to analyse existing safety features and the newest advancements in the field. Here, the aforementioned synergies equally come into play. It is recommended, that any conflict between safety and security be avoided and that a particular focus is given to those systems that serve both or even all 3S (IAEA, 2016a).

The design and construction, as well as the operation of the plant are equally important for safety. Through the integration of passive systems, human errors can be reduced or avoided and safety is enhanced. (International Nuclear Safety Group, 2010)

The idea of "*inherently safe reactors*" (Forsberg & Weinberg, 1990), is outdated. While reactors cannot be "*inherently safe*", they can be enhanced through safety systems. These can be active or passive, depending on whether "*they rely on external mechanical and/or electrical power, signals, or forces*" (Forsberg & Weinberg, 1990).

The three major nuclear accidents, namely Chernobyl, the Three Mile Island, and Fukushima have all led to a core meltdown. Preventing such situations is one of the highest priorities of nuclear safety efforts, so as to prevent public concern. Active systems alone are not enough to ensure increased safety. They not only have a limit above which further enhancement is not feasible anymore but are also susceptible to human error. Gen-IV reactors have the integration of passive safety features as one of their goals. (Tripathi et al., 2020)

Passive safety systems in consequence, rely on natural laws like gravity or changes in pressure. As it became ever-more evident through the Fukushima accident, the necessity of passive safety features is crucial. Controlling what is happening within the containment during accidents is near to impossible, but passive systems can be accessed from outside. In the past, many safety features were dependent on power, this is not the case with new generation reactors. The passive safety systems can be integrated into the design of new reactors such as Gen-IV or SMRs. The passive safety features shall be for enhancement purposes and not replace the basic safety features. (Chang et al., 2013)

An example of a passive safety system is the 'Decay Heat Removal System', which ensures emergency cooling (Tripathi et al., 2020). In accident situations, decay heat can be removed through natural circulation (Puppo et al., 2021).

Safety enhancements through the design of an NPP also include the structure of the plant and the materials used, like concrete to strengthen the containment in case of an accident. At the design phase, systems "*such as the emergency core cooling system, the emergency clean-up system*" (IAEA, 2016a) are integrated. Characteristics like separate safety functions and redundancy are what make the NPP reliable. (IAEA, 2016a)

Fault tolerance, which is closely related to the 'single-failure criterion' mentioned earlier, is another important aspect in the design of the reactor. It is the ability of the system to continue operation even if one component fails. To this end, redundancy is necessary within the design. (Pham & Galyean, 1992)

Redundancy is the inclusion of extra spare parts or equipment which can be used in case another fails to perform (ENS, 2019). Redundant systems are present in control as well as in communication systems (Pham & Galyean, 1992). Finding the right number of redundancies can be challenging and optimisation in this regard is complex as it comprises various factors (Pham & Galyean, 1992).

The problem of redundancy optimisation is similar to others related to the big amount of data that needs to be analysed. AI could support such optimisation processes, as has been proved, evolutionary algorithms such as GA (genetic algorithms) and PSO (Particle Swarm Optimisation) have been used for allocating redundancies. (Busse & Moreira, 2021)

To enhance safety in NPPs, it is important to incorporate robust features already into the design process of reactors. Through modelling, a reactor's response under extraordinary emergency conditions can be tested. Safety assessments serve to predict future issues and prevent them through countermeasures. Simulations play an important role in the design process, as the evaluation of various configurations can support enhanced safety. (Wang et al., 2024)

In light water reactors for example, thermal-hydraulic modelling evaluates the behaviour "*of coolant and heat transfer*". Gaining insights about the core's thermodynamics is important for design optimisation and enhancing safety. (Wang et al., 2024)

As small modular reactors (SMRs) are in the early stage of deployment and hence at the forefront of political discussions, their economic viability is highly emphasised, as they are more time and capital efficient, and could include new technological advancements in their construction. As mentioned by Albert (2024), a Purdue university study demonstrates how the integration of AI within O&M can help reduce the costs during that operational stage. (Albert, 2024)

Concerning radiation, AI can monitor in real-time and help the control of hazards within NPPs, ultimately ensuring a higher level of safety (Arhouni et al., 2025). Genetic algorithms can also help design radiation shielding for SMRs (Ejigu et al., 2024). As SMRs are gaining popularity, it is anticipated that next generation reactors will incorporate intelligent safety systems such as AI to enhance the plant operation (El-Sefy et al., 2021). Further, AI may even remotely control NPPs such as SMRs (El-Sefy et al., 2021).

As mentioned earlier, integrating safety features into the design holds promising opportunities (Iturria & Li, 2022). While enhancing safety can lead to increased investments, SMRs appear to be the most cost-efficient and promising option (Hassan et al., 2023). Particularly in the research of SMRs, AI is a crucial emerging topic.

SMRs are characterised by their compact nature, smaller in size as well as in capacity compared to other nuclear reactors. SMRs are believed to be safer and easier to deploy and able to meet the increasing energy demand, without emitting carbon emissions (Wang et al., 2024). Additional advantages of SMRs are their scalability and flexibility, their cost savings from a long-term perspective and the reliable base-load power supply (Yurman, 2024).

It is important to note, that with increasing digitalisation, comes a higher dependence on power-dependent systems. Nevertheless, passive systems and redundancies must not be overlooked because of the development of faster and more efficient solutions which can only operate when electricity is provided. As AI systems rely on electricity supply, it may not be of use in cases of power outage.

The dependence on electricity is a limitation which must be considered when exploring AI's potential in the nuclear energy field. AI requires a lot of power, so a constant supply needs to be provided. It is hence important to maintain the enhanced safety features of Gen IV, such as the passive safety components and that these may also be enhanced through AI in their design. The passive safety features are meant to work even without power supply, hence they can only be improved through optimisation during the design process.

4.4 How can AI be implemented to enhance Safety in NPPs

This section will examine the technical integration feasibility of AI within nuclear operations. Technological advancements in various fields, drive the integration of AI in NPPs with the purpose of enhancing safety and efficiency. Although, real-life application of AI within the nuclear field is still limited (Ejigu et al., 2024), the American Nuclear Society argues that AI integration into NPPs can "*significantly reduce operating costs and improve [the] ability to make better decisions*" (ANS, 2023).

The advances in autonomous learning, with the self-support mechanism of AI opens up new opportunities in the energy production, particularly nuclear energy (Karim & Muhammad-Sukki, 2023). Various international organisations and institutions such as the European Commission's formerly called 'Euratom', the OECD's nuclear energy agency, as well as the IAEA are considering AI's potential in the nuclear sector (Karim & Muhammad-Sukki, 2023).

Artificial Intelligence developments in recent years have brought a number of opportunities in various sectors, but at the same time may also bring in new challenges. AI as a term summarises different advanced technologies and supports industries in reducing their costs and improving their competitiveness. Therefore, AI plays an important role in terms of safety and viability of NPPs. (Huang et al., 2023)

AI is believed to be useful for the operation and control of NPPs and ensure stable safety (Wood et al. (2017) as cited by Hassan et al. (2023). Real-life AI applications within the nuclear industry are limited, but a number of experiments and studies demonstrate its potential. (Huang et al., 2023)

The IAEA grouped the nuclear domains in which AI can have a potential positive impact. The topics are automation, optimisation, analytics, prediction & prognostics and insights. In terms of automation, AI will increase the reliability and reduce human errors. Automation may reduce the time of operations and even reduce the radiation exposure. Operations of NPPs include the staff inspecting the plant conditions, in this regard, together with robots or drones using computer vision to analyse their environment, the staff's physical checks are rendered unnecessary. By reducing the human's workload, the likeliness of human error is also reduced. Nevertheless, human-computer interaction is essential and needs to remain established in the control room. (IAEA, 2022)

Optimisation is inherent to AI tools such as deep learning and hence to machine learning, through classification and prediction, DL is able of enhancing analysis capabilities significantly (Ongsulee, 2017). AI has demonstrated it can optimise various sectors through enhancing productivity and by "*automating repetitive tasks*" (Issa, 2024). Automated operations and enhanced decision-making are characteristics of AI systems which use the "*self-correction*" and the "*self-optimization*" method (Mata et al., 2018).

4.4.1 Design

Especially with the recent deployment of SMRs, the integration of safety, alongside security and safeguards features within the design is possible (Iturria & Li, 2022). Using AI during the design phase can be crucial in efforts to enhance safety. Research focuses on accident-tolerant fuels and on materials that are more resistant to oxidation. The goal is to both increase conductivity of the fuels and at the same time contain products within the pellets. If damage occurs, there may be "*hydrogen explosions and radionuclide release*", related to the exposure of Zr (zirconium) alloys to high temperatures (Hassan et al., 2023). Genetic Algorithm (GA) is very useful in the design process of nuclear reactors, such as the design of SMR's radiation shielding. (Ejigu et al., 2024)

AI could be used for optimising various components through simulation. While rarely used as of now, research is underway for supporting the use of AI in the development of accident tolerant fuels (Hassan et al., 2023).

In terms of scientific research, the possible applicability of AI in supporting discoveries is also put forward. The groundbreaking possibility of applying AI for potential future discoveries, through the use of LLMs could positively impact the design of NPPs. (Novikov et al., 2025)

Particularly in the field of nuclear material research AI can be employed, for the modelling of material behaviour under various conditions. The goal is for future reactors to be constructed with advanced materials. Most importantly, a lot of effort is invested in optimising the core of the NPP. (Hassan et al., 2023)

The nuclear reactor core is one of the most important parts of the NPP to be designed. Implementing AI systems to optimise it, holds promising prospects for nuclear safety. Sobes et al. (2021) believe that AI-based design is going to be an important if not the essential tool used for design-purposes, leveraging optimization algorithms and ML models, together with other important technological developments, resulting in safer energy production. (Sobes et al., 2021)

4.4.2 Regulatory & Licensing

On the one hand, from the government's point of view, AI could support the regulator in defining the safety requirements to be met by the operator. On the other hand, from the operator's point of view, regarding SMR deployment in particular, AI could significantly reduce the regulatory review process time, which could usually take years (Yurman, 2024). This can significantly reduce the related costs and encourage higher safety at the same time.

ML can support the safety assessment process in NPPs regarding fire hazards or seismic risks (Ejigu et al., 2024). This can support the licensing efforts and ensure all requirements are met.

Through safety recommendations and setting adequate standards, AI can enhance safety regulations. By identifying anomalies or non-compliance AI can also speed up licensing processes and ensure the deployment of safe reactors only, reducing human oversight mistakes.

4.4.3 Maintenance

AI is used in many industries, for analysing sensor data which monitor equipment. The monitoring produces immense amounts of data which AI can process much quicker than any operator could. (Aldoseri et al., 2024)

The safety of nuclear reactors is arguably the most important aspect, hence safety assessment is a regular process in meeting safety standards, by integrating AI into this, the reliability can be enhanced. Further, AI supports the maintenance of NPPs through monitoring, predictive maintenance and automated decision-making. AI technologies may also propose actions to solve any issue at hand. Examples mentioned by Arhouni et al. (2025) comprise adjustments of control rods or of the coolant flow. In regard to abnormal temperatures or a change in pressure, AI is also able to provide timely alerts. (Arhouni et al., 2025)

Through preventive maintenance the NPP's lifetime can also be prolonged (Aldave De Las Heras et al., 2024). But with prolonged lifetime, may come degrading issues, which may lead to increased risk of future failure (Huang et al., 2023). In addition, the reliance on preventive maintenance leads to excessive maintenance and redundant costs, AI can help predict degradation (Huang et al., 2023) and recommend maintenance when necessary. As Aldoseri et al. (2024) note, AI is able to indicate signs of deterioration which allows for a replacement or repair, before any failure occurs. Aldoseri et al. (2024) argue that this reduces unscheduled downtimes and hence reduces costs as emergency response come at higher costs.

AI within prediction and prognostics, can be of good use for maintenance activities. Unexpected downtimes can be reduced, and timely maintenance can be planned ahead through prediction of useful life. The advantage of AI in this regard, is the improved prediction accuracy, as it is capable of using non-linear data-driven methods. (IAEA, 2022)

An example success story of integrating AI in autonomous control systems of NPPs is mentioned by Arhouni et al. (2025), in which the case study showed the capability of the model to correctly predict the increased temperature at the centre of the fuel rods in the reactor, in case there was an accident which hindered the coolant pumps from working as usual. This knowledge can be of crucial importance when responders are expected to react during a failure. This case study also evidenced the resilience of the model against any irrelevant variations, hence providing reliable assistance in autonomous systems (Arhouni et al., 2025). When AI sets goals in an autonomous manner, this may also lead to unexpected results as they were not defined by humans (Cha, 2024). This could have negative effects which will be discussed later on. ANNs can also be employed for the analysis of the thermal performance of an NPP and what variables impact it (Gomez Fernandez et al., 2017

Various maintenance tasks at NPPs are putting human operators at risk but could be automated. While the completely autonomous decision-making of AI systems should still *be critically assessed, many routine operations could be replaced by robots and AI system assistants. AI systems are efficient in detecting anomalies and can indicate where maintenance is needed. Particularly in high-risk zones they could replace humans.*

4.4.4 Monitoring & Prediction for Decision-Making

In NPPs, online condition monitoring (OLM) is used to monitor safety parameters and provide references to operators for corrective measures and for prediction of conditions of the plant. A novel approach to OLM has been enabled by the recent development of digital twin technology, which allows for dynamic, real-time comparisons between the digital and physical replicas of NPPs. Digital twins are able to assess normally inaccessible data of the plant during operation. (Huang et al., 2023)

Digital twins are equally gaining attention, in nuclear energy, as in other fields. Digital twins are believed to increase not only safety but also efficiency of NPPs (Kochunas & Huan, 2021). Digital twins can make use of AI and ML models (Hassan et al., 2023).

Neural networks applicability within monitoring processes is being researched (Hassan et al., 2023). The feed-forward backpropagation ANN is already utilised in some PWRs to estimate the core parameters for optimisation of the fuel reloading patterns (Kim et al. as cited by Ejigu et al., 2024). In a study from 2021 for example, the feed-forward backpropagation ANN was "*trained to simulate the interaction between the reactor core and the primary and secondary coolant system*" as well as other integrated complex systems. As a result, the ANN performed well, when comparing it to the SD (system dynamics) model. The steam pressure and the temporal fuel temperature estimates varied only very little (up to 1.6%) and their respective distributions match those of an SD. (El-Sefy et al., 2021). While various neural networks are being researched, within the nuclear industry, a clear focus remains on the backpropagation ANNs. (Hassan et al., 2023)

The simplest ANN is the feed-forward backpropagation process, in which data moves only in one direction, from input to output. The ANN is trained on data from a PWR SD model. In NPPs the ANNs have been used for prediction purpose for different power inputs and accidents related to reduced flow. ANNs can also model complex relationships and adapt through learning, for supporting plant-management through monitoring and analysis. An ANN which learns from historical time-series data is the Recurring Neural Network (RNN). (El-Sefy et al., 2021)

Another model showing improved efficiency in supporting monitoring efforts of operators is the DNN (deep neural network) in which reactor vessel water levels are predicted during severe accidents, as this is something that is difficult if not impossible to measure for operators. The DNN can help fill knowledge gaps in case of instrument failures and provide the operators with crucial information during emergencies. The model showed improved accuracy in comparison to previous systems and is confirmed to be a reliable safety enhancer. (Do Koo et al. as cited by Arhouni et al., 2025)

Overall, neural networks can support operators of NPPs in various aspects, such as monitoring, sensor failure detection, and management of abnormal conditions through classification (Hassan et al., 2023).

Traditional thermal-hydraulics are not as efficient as they could be with the integration of ML, for the purpose of accelerating substantial computation model methods. ML technologies can predict parameters which are important for decision-making during operation, such as knowing the critical heat flux is fundamental for safely operating reactors that are water-cooled. (Huang et al., 2023)

Other information that can be derived from thermal hydraulics models is the behaviour of the coolant in certain situations (Wang et al., 2024). The coolant's movement and heat transfer can be predicted and support the operator.

In 2019, Purdue University was the first to install an "*all-digital nuclear reactor system*" (Wiles, 2019) in the US. Advanced technologies are considered to increase safety, as they may recognise any performance issues ahead of the initially planned maintenance window. Currently there exist no 100% digital control systems of NPPs but the Purdue reactor serves as a pioneer example for future applications. (Albert, 2024)

Genetic algorithms (GAs) can enhance performance, through the function "*of remembering solutions successfully used in the pasts*" which worked already Mata et al., 2018).

Zeng et al. (2018) as cited by Arhouni et al. (2025) have created a performance prediction model system that is ML-based to support autonomous control of small reactors, as mentioned before also here thermal-hydraulics model simulations are being used. ML builds a model for making predictions and can support the decision-making process (Ejigu et al., 2024).

4.4.5 Early Warning and Anomaly Detection

AI can also support nuclear operations in the early detection of anomalies and the enhancement of the efficiency of the power generation, through minimising energy waste. When anomalies get detected early enough, operators have the opportunity to react in a more timely manner. If operators make a mistake, this can also be identified by AI systems. (Ejigu et al., 2024)

For early warning, knowledge on the steam pressure and the reactor fuel temperature is essential. Early warning systems are crucial in risk mitigation, as they have the ability to forecast the nonlinear behaviour of the system and its subsystems. They serve as supporting tools for operators in their decision-making process during operation and emergencies. (El-Sefy et al., 2021)

4.4.6 Fault Diagnosis & Emergency Response

ANNs could be applied for supporting plant operators during reactor failure. Through modelling of fuel rod temperature, this tool can detect resistance temperature detector sensors malfunctions. According to Ejigu et al. (2024) ANNs are efficient tools for identifying nuclear reactor transients during operation for enhancing safety. Nevertheless, these tools are only potential technologies which could be used for improving assets and for state predictions of nuclear reactors. Most importantly, they may be employed for quick emergency response, in analysing the situation and all its components rapidly. Deep learning (DL), another form of ML, whose algorithm is based on the ANN can also be used for diagnosing faults. (Ejigu et al., 2024)

ANNs may also enhance risk mitigation under abnormal conditions, by supporting decision-making of operators. In case of an emergency, analysis of the big data which is collected at NPPs can help the operator in making informed decisions. (El-Sefy et al., 2021)

Argonne National Laboratory of the US DOE (Department of Energy) have demonstrated how NPP operators could be supported by generative AI in their decision-making process. Their aim is to simplify diagnostic data for the operator and presenting what is wrong and why and what an adequate response may be. They developed a tool called PRO-AID which identifies faults and connected it to an LLM (large language model) which then interprets the data and presents it to the operator. The tool compares the processes of the NPP to expected behaviour and alerts any fault in case of a deviation. In combination with the LLM, complex data and information can be simplified and help the operator, this "*has the potential to enhance the training of our nuclear workforce and streamline operations and maintenance tasks*" (Rick Vilim as cited by Clark, 2024)

ANNs can be used in various ways within an NPP. They were used by researchers for fault detection through monitoring (Gomez Fernandez et al., 2017). Different from traditional ANNs, dynamic neural networks are more effective in identifying and locating transients as well as their gravity (Huang et al., 2023).

Machine learning is a breakthrough in fault diagnosis (Ejigu et al., 2024). Dave et al. (2024) argue that understanding why and how something is wrong, is especially important when it comes to NPPs. This explainability aspect is especially important for NPPs where not only the identification of a fault but understanding the origin of it are crucial for operators. AI's self-diagnosis may be employed in fault diagnosis when using optical access networks (Mata et al., 2018).

Not only during O&M sensor faults can be detected, but AI is also able to identify component faults in nuclear equipment (Reifman, 1997). Fault-diagnosis is possible on both the system and the component level and may be the most active use of AI approaches in nuclear related domains to date (Huang et al., 2023).

In Fukushima for example the issues in emergency response were drastic, AI could have supported through immediate automatic response. Immediate automatic response should be assessed carefully though, as full autonomy of AI systems could have negative effects too, this must be further examined.

4.4.7 Optimisation

Optimisation is inherent to DL and hence to ML and AI, through classification and prediction, DL is able of enhancing analysis capabilities significantly (Ongsulee, 2017). AI has proven that it can optimise various sectors through enhancing productivity and by "*automating repetitive tasks*" (Issa, 2024). AI can be used for automating operations and enhancing decision-making through AI systems which use the "*self-correction*" and the "*self-optimization*" method (Mata et al., 2018).

Some evolutionary algorithms (EA) such as the genetic algorithm (GA) are believed to support optimisation of complex nuclear systems (Huang et al., 2023). Ga is believed to have multiple applications, for example in optimising the reloading process of fuel assemblies, or in simulating the reloading patterns (Ejigu et al., 2024). For energy not to go to waste, GA can also support in optimised energy management. (Ejigu et al., 2024)

The particle swarm optimisation (PSO), another form of evolutionary algorithm, can also be used for fuel reloading in PWRs and for recognising patterns in VVERs (water-water energetic reactors), as well as for optimisation of marine NPP's secondary circuit systems. PSO is also applied for optimising control drums of microreactors (Ejigu et al., 2024)

To efficiently integrate NPPs with the electricity grid, AI can significantly support in stable load management (Ejigu et al., 2024). AI can predict demand to optimise fuelling processes within the plant (Yurman, 2024). Through this output maximisation, operational costs can also be reduced.

For a better understanding of the relation between the AI capabilities and the safety component, a matrix was built, demonstrating which areas are directly linked:

Table 2: AI Relevance Matrix for Nuclear Safety (own work)

	Design	Regulatory	Operations & Maintenance	Monitoring	Anomaly Detection	Fault Diagnosis	Emergency Response	Licensing
Simulations & Digital Twin	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔	✔✔	✔✔✔	✔✔✔
Pattern Recognition	✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔
Autonomy	✔	✔	✔✔✔	✔✔✔	✔✔	✔✔	✔✔✔	✔
Decision-making Support	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔✔✔	✔✔✔	✔✔✔
Optimisation	✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔✔✔	✔✔✔
Prediction	✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔	✔
AI sensors/ robots	✔	✔	✔✔✔	✔✔✔	✔✔✔	✔	✔✔✔	✔

The number of ticks in the matrix is intended to visualise the relevance of the specific AI within the indicated area. One tick stands for limited applicability, two ticks indicating a good potential for application and three ticks indicating very strong safety enhancement possibilities.

The matrix visualises the applicability of various capabilities of AI systems within safety-related domains of NPPs. AI Simulations & Digital Twins are one of the most promising applications which can enhance safety in all of the above-listed categories. Safety design can be enhanced, and regulatory processes may be improved, resulting in more robust and reliable NPPs in terms of safety. Enhanced maintenance and monitoring through AI can prevent major damages and emergencies. Detecting and diagnosing anomalies and faults is important for preventive purposes. And finally, simulating emergency responses is crucial for responding adequately to high-risk situations.

Key components of nuclear safety are engineered safety features, control systems, operation limits as well as conditions for safe operation. Further, aspects such as human factor engineered and licensing for regulatory purposes are equally important. All of these components are covered by the matrix.

While some areas are impacted less than others, there exists a potential in many. Particularly the areas with three ticks should be further explored, to identify the most promising applications of AI. Operations and maintenance as well as monitoring are the safety-related areas where AI seems to have the greatest potential.

4.5 Identified Advantages of AI

Overall, it has been demonstrated that various opportunities exist, for enhancing safety of NPPs through the application of AI. This chapter will summarise these and other relevant benefits such as efficiency and cost reduction.

While many advantages are well established, they only show the potential for AI applications in enhancing safety at NPPs. There are so far no real-time examples of full AI integration into this field. It is hence important to note, that the presented advantages require further critical examination and consideration.

4.5.1 Enhanced safety through optimised design

Technology advancements in the field of AI in optimisation of the reactor's design for enhancing safety, all while reducing costs is more than promising (Huang et al., 2023). AI can optimise passive safety systems and redundancies to improve the reliability of reactors. The materials used for construction and containment can also be improved, through the support of simulation processes. Gen-IV designs, for example, produce less waste and are more efficient as they include materials that enhance safety (Zohuri & Mossavar-Rahmani, 2024).

The design phase is of great importance for ensuring safety of NPPs during O&M. Many safety features are integrated during this phase. Optimisation and modelling during design processes help enhance safety, these may be enhanced through AI as demonstrated above. What constitutes safety at NPPs are the materials used, in this regard AI can help in the material research and by simulating various materials under different conditions in a more efficient and less risky manner. AI can speed up the processes in designing the Gen IV reactors, whether it is in simulating which are the best materials or whether it is about the design of the plant itself. AI has great potential in this regard, as it can assist *in simulating the behaviour of materials and structures for best resistance and higher safety.*

4.5.2 Enhanced Safety through Risk Prevention

In terms of safety, AI can help identify hazards at NPPs and support the analysis of data outputs. AI applications encompass areas such as problem solving and decision-making, self-teaching, data analysis and prediction, and finally recognition of speech or images. (Arhouni et al., 2025)

Through the early detection of anomalies, risks can be reduced. For example, AI can be useful in recognising initiating events, which is of utmost importance to prevent serious dangerous events (Arhouni et al., 2025).

Human error, which can also be the root cause of accidents can be avoided through the integration of AI in the monitoring and the decision-making processes. Human errors can occur due to oversight, fatigue or mistakes made by humans.

ML can support the safety of NPPs and ultimately increase the lifespan of the plant by studying past trends and based off them, predict possible issues and where they may arise, this is invaluable for accident management. It would be beneficial to promote open-source data on past accidents from various NPPs, to prevent similar accidents in the future.

4.5.3 Enhanced Safety through Autonomisation

Integrating AI into robots can protect humans through reducing their exposure to radiation, by replacing the operator for dangerous tasks. Autonomisation can further prevent oversight by humans, as AI could be implemented for emergency response purposes.

4.5.4 Enhanced Safety through Decision Support

Particularly during accidents AI can support operators and help to ensure operational safety. Decision-making in NPPs is complex, in this regard AI serves as a decision support system (DSS) in O&M to protect humans and the environment (El-Sefy et al., 2021). During safety-critical situations it is crucial to be well-informed in order to make the right decision. AI is able to support the operator in those situations with quick analysis of vast amounts of data. Something a human would simply not be able to do, especially not in such a fast manner. During emergencies, early response can make an important difference.

AI enables a shift from models based on observation, to models based on data, this provides benefits like better efficiency, lower costs, and a greater ability to handle new or unexpected situations (Arhouni et al., 2025) which can enhance safety preparedness.

Neural networks are believed to support operators in handling transient events through problem-solving and making use of big data (Hassan et al., 2023).

Overall, AI systems can support the human operators in the decision-making in various ways. By simultaneously analysing information from various sensors, cameras and radars, AI is much quicker in making sense of the big data and can then recommend the operator in future tasks. In this regard natural language processing could be very useful for enabling the operator and the AI system to interact in real-time.

Seeing as the human operator may not dispose of all information, AI can assist the operator in diagnosing faults and identifying the origins which is crucial in decision-making during emergencies. AI is also quicker and much more efficient when it comes to emergency response, this is another potential advantage of AI integration within the field.

4.5.5 Enhanced Safety through Monitoring

The detection of objects can be useful during nuclear safety monitoring, as spatial awareness is crucial in such high-risk environments. Visual inspections and monitoring of equipment and staff could be enhanced. At the Three Mile Island for example, a simple *mistake like a post-it, covering critical indicators, can lead to misinterpretation from the operators. If AI were to be included, potentially replacing the control room, or at least enhancing it, such mistakes could be avoided.*

Further, any damage detection efforts could be automated and occur in real-time, even in high-radiation areas, through the support of robots for example. At Fukushima, the limited access was a challenge for the adequate response, autonomous robots including AI systems could have assisted in the management, and immediately alert where or when an issue occurs. At various accidents, the poor monitoring was a problem. Also, the safety of operators can be ensured by monitoring their compliance with safe zones and preventing any accidental exposure to radiation.

4.5.6 Make use of Big Data

AI algorithms are modelling techniques that are based on data input making it heavily reliant on high-quality data. The data that is generated by NPPs is huge and its interpretation requires time and effort. It is a challenge for traditional methods to make use of this big data, hence the AI possesses an advantage in overcoming this obstacle. Through improved performance and operations optimisation, AI can also make NPPs less environmentally harmful. (Ejigu et al., 2024)

Various systems within NPPs are monitored simultaneously and at all-times, leading to enormous amounts of data (El-Sefy et al., 2021). AI needs to integrate big data and IoT devices. There is a synergy between AI, IoT and big data which has great potential for NPP's O&M safety (Ejigu et al., 2024).

AI can make use of big data in a way that was traditionally not possible and can enhance both monitoring processes as well as safety protocols. (Arhouni et al., 2025)

The large amount of data generated by NPPs is often difficult to analyse simultaneously for human operators. AI can support in this regard, by making sense of big data and presenting it to the operator in an understandable manner. AI is capable of collecting data from different parts of the reactor and connecting them, making room for better *informed decision-making. Humans have difficulties comprehending such complex systems of systems.*

4.5.7 Enhanced understanding of the reactor (knowledge preservation)

With the longer lifetime of NPPs, some negative aspects may arise, which will be discussed later, such as the workforce leaving while the plant is still in operation and hence taking with them first-hand expertise. AI instead, is able to preserve information for many years and make use of it immediately if necessary, unlike humans, AI systems do not "forget". AI systems can therefore be a valuable information source within NPPs.

4.5.8 Improved Simulation

An important part of nuclear safety relies on simulation processes. Real-life experiments may be costly and difficult to conduct, hence simulations are being employed. AI can enable real-time simulations through pattern recognition and predicting output. This speeds up the process significantly.

Digital twins play an important role in enhancing safety at nuclear reactors, as normally inaccessible compartments are made accessible, even if only digitally.

For Fukushima for example the barrier was too low, related to a lack of appropriate simulation and risk assessment. Using historical data dating back earlier, AI might have been able to predict the related increased risk, which humans did not identify.

4.5.9 Reduced Costs

AI could extend the lifespan of new reactors which can drive down costs (Zohuri & Mossavar-Rahmani, 2024). Further, through speeding up and simplifying operational tasks and replacing workforce, costs are also reduced.

While on the one hand, operational costs may be reduced, capital investments might be increased through higher spending for AI integration. Using AI systems in the design *phase or developing algorithms may be a costly initial investment that should be taken into account.*

4.5.10 Enhanced Efficiency

The application of AI within NPPs has various potentials such as enhancing safety and reliability but also increasing overall efficiency of the reactors. Efficiency can be measured in human, time or capital input relative to the output. The safety improvements enhance the efficiency of NPPs by reducing the time that operators need to invest in routine operations that can be time-consuming.

ML can increase the learning speed and have enhanced understanding of complex non-linear data due to improvements within the management of big data (Gomez Fernandez et al., 2017). In the context of load forecasting, AI can predict accordingly and support planning efforts.

Arhouni et al. (2025) suggest that future production of energy, inter alia, will be strongly impacted by the technological advancements in the field and that through AI's support in rendering neutronics as well as the thermal-hydraulics models simpler can support in making NPPs safer and the improved methods for risk detection also help strengthen safety.

While AI is still rarely actively being used in NPPs nowadays, it is still very much used in other industrial processes and has demonstrated its positive characteristics of improving the society's quality in various aspects (Cha, 2024). Tasks such as optimisation or problem solving are an easy task for AI, which sets goals and subgoals to reach an overall goal. Though, with it also comes the aspect of unpredictability, which will be discussed later on (Cha, 2024).

Overall operation of the system is improved through prediction and optimisation (Ejigu et al., 2024). More importantly, AI is capable of overcoming various challenges, such as analysing big data and adapting to dynamic conditions and suggesting solutions even for unknown scenarios. (Mata et al., 2018)

Efficiency of NPPs is increased, by speeding up processes, and by reducing the human workforce needed for operations for running the plant.

4.6 Challenges and Limitations

This section will discuss the key challenges of AI applications within the nuclear sector. Issues such as data reliability, quality, security or privacy shall be considered, as well as regulatory compliance. Further, the AI's missing transparency and interpretability remains an obstacle when it comes to AI implementation in any field. With the adoption of AI also come substantive investment costs and the need for training of personnel that demonstrates AI literacy. (Ejigu et al., 2024)

When considering the usage of AI within any type of nuclear application, it is important to consider various fields such as ethics and accountability. While it would be beneficial to have a regulatory framework on an international level, it is recommended to consider this issue on a national level. On the one hand, AI integration in the field of nuclear technology presents a lot of possibilities but at the same time brings important risks that need to be taken into account. (Ajaykumar, 2025)

4.6.1 Ethical Concerns

AI has various ethical challenges that may raise concerns regarding safety and should be addressed. An important aspect of AI integration is the holistic approach with experts from both fields, of nuclear and of AI (Arhouni et al., 2025). AI is likely not to take ethics into account in its methodology of finding the optimised solution, this characteristic must be taken into account (Cha, 2024). It is difficult for AI to reflect human's intentions and their values in its decision-making and ultimately in the outcome. Oftentimes AI does not take into account ethics and is too focused on reaching the goal or fulfilling the subgoals (Cha, 2024).

Some ethical concerns regarding the application of AI to any industry, not only the nuclear sector, is that of AI's possible "*transgression of human rights, and human values, such as dignity*" (IAEA, 2022). It is important to address AI's possible biases and issues regarding accountability and transparency (Abuzaid, 2024). Neural networks are sometimes called ‘black boxes’ as they are difficult to interpret due to hidden layers and their structure of nodes (Phillips-Wren, 2012).

The autonomy of AI in setting goals and sub-goals leading to unexpected results that was mentioned earlier, is problematic as it may lead to AI making unethical decisions that would not have been taken by humans and leading to dangerous behaviour putting humans at risk (Cha, 2024). The integration of various new systems within nuclear operation processes has as a consequence the increased complexity of the “*human-machine interactions*” (Gomez Fernandez et al., 2017).

As AI takes decisions it does not take into account human values, which could put at risk both humans and the environment. This challenge should be further explored, not only in regards to applications within the nuclear field but regarding AI applications in various fields.

4.6.2 Data Issues

Not only ethical issues are of concern but also worries about the quality and quantity of data play an important role. While it may be difficult to collect enough valuable data, it is necessary that the collected data is of good quality in order to ensure accurate and effective functioning of AI systems, which receive this data as input (Arhouni et al., 2025). The data used for training AI often comes from simulations rather than real-world events, as the costs and risks of acquiring experimental data is high (Huang et al., 2023). Another challenge in collecting the data is the rarity of certain nuclear events and hence the difficulty of collecting data on them or the errors that may occur during measurements. (Arhouni et al., 2025)

One of the biggest hurdles in regard to AI applications is data. It is expensive to annotate and curate and prone to bias. Although the time to train the models is significantly reduced, the time needed to refine the dataset in order to avoid future biased output and guarantee reliability is immense. Instead of focusing research on model performance improvement, there needs to be efforts aiming at cleansing the data, as even a small improvement of the data can lead to higher reliability, instead of training it on noisy data.

Effective data design can help mitigate bias and tools such as data augmentation and AI evaluations are used to ensure reliable results. (Liang et al., 2022)

Data augmentation can help tackle the issues of overfitting and underfitting (Ejigu et al., 2024). To ensure that AI is usable, data usability is fundamental and is defined by the data being usable (size is sufficient for example), relevant and of high quality. (Mosqueira-Rey et al., 2023)

As AI is basing its decision on the input it is provided only, it is crucial to ensure that the input data valuable. Collecting data of nuclear power plants can be costly and difficult. While various methods can help overcome this challenge, it is important to take this limitation into account.

4.6.3 Bias

A prevailing problem with AI in this field might be that of the over reliance on technologies which might have built-in biases and make mistakes that the operators then do not notice. Being dependent on automation and replacing workforce with AI systems is another challenge, which needs to be addressed, potentially through according policies. (Issa, 2024)

ML is not provided with patterns or rules but creates them independently, based on the data it is given. The problem which arises, is that humans may not be able to understand why the AI gives a certain output, raising concerns of explainability and transparency as well was accountability. Ethical concerns of AI within nuclear, encompass fields such as autonomy, bias, transparency and the need for regulatory frameworks. (IAEA, 2022)

If AI does make a mistake or makes an unusual decision, apart from the outcome, this raises the problem of unpredictability mentioned before. This major concern is caused by the complex autonomous subgoal generation of AI. Different to the bias, this has got nothing to do with the way the AI was programmed or trained but rather on its working mechanism and on how it interprets the most efficient way to solve a problem. This might significantly differ from normal human behaviour. (Cha, 2024)

As Pluff and Nair (2023) put it "*Biased people produce biased products*". Algorithmic bias is a significant problem that shouldn't be overlooked. Since AI systems learn from the data they are trained on, any bias present in that data will be reflected in the AI's outputs as well (Pluff & Nair, 2023). AI models that were designed to detect radiation might for example possess a bias if the data they were trained on did not cover the full spectrum of sources of radiation. (Arhouni et al., 2025)

Based on the functioning of AI algorithms, any bias in the input will result in a biased output. It is hence important to acknowledge this issue by ensuring datasets which will be used as input are representative and will not lead to unwanted results.

4.6.4 Transparency & Explainability

Explainable AI models are crucial in safety in order to improve analysis and response as the output is provided to operators for decision-making (IAEA, 2022). One big challenge that remains is that of how to efficiently combine all resources and data for AI to be able to make the right decisions (ANS, 2023), while remaining explainable to the operators.

Explainability is crucial, and while often not given, in terms of ANNs can be attained by either relating inputs to outputs through Pearson correlation or through adding a visual information flow between the layers of DNNs (Dave et al., 2024).

Transparency and explainability remain some of the key challenges for AI applications. In order to integrate an AI system into high-risk industries such as the nuclear power industry, it is crucial that the system be reliable. With a lack of explainability this is difficult to achieve. This area must be further researched to ensure that the human operators can make sense of the AI system's decision. This is crucial not only for the application within the nuclear sector but any industry which integrates AI.

4.6.5 Security Risks

With increasing digitalisation of processes at NPPs comes the increased security risk of cyberattacks. This shows the importance of the synergy of the 3S and how it is impossible to address one field without addressing the other. Kuznetsova and Fionov (2022) as cited by Cha (2024) conducted a study about information security systems at nuclear facilities and highlighted their increased susceptibility and exposure to attacks, resulting in weaker security, and underscoring the need for a regulatory framework in this field. While having international regulations set by the IAEA is important and necessary, it should also be considered, that it is difficult to enforce them, and that AI continuously evolves and changes. (Cha, 2024)

Autonomy in digitalised processes, is an important topic too and while it offers opportunities in improving efficiency but at the same time it brings uncertainty and risks. On the one hand, the speed of tasks can be significantly increased as well as constant surveillance can be achieved more easily. On the other hand though, with autonomisation, comes a growing risk of cyberattacks. (Boulanin et al., 2020)

DL models, such as DNNs, which have demonstrated great potential, can be misled through deceiving images and hence make wrong assessments. An example mentioned by Huang et al. (2023) is the misclassification of "*red and white lines as a baseball*". This issue prompts concerns about the robustness of AI technologies and whether they are resilient enough to withstand such attacks.

As safety is closely intertwined with security as well as with safeguards, it is important to consider any unwanted increase in security risks through the enhancement of safety features. As mentioned earlier, it is possible that one area is enhanced to the detriment of another area.

4.6.6 Liability & Regulations

Finally, also liability plays a significant role in AI applications. This topic is widely discussed in various fields, particularly in autonomous driving, but it should be an equally important topic for any field, implementing AI systems. If autonomisation and independent decision-making become a norm within NPPs, and are achieved through AI algorithms, it is important to evaluate who will be held responsible in case of an unwanted outcome or accident. No national or international regulation recognises AI to be a legal person, hence it cannot be held responsible for any damages. (Čerka et al., 2015)

As the development of robust regulatory frameworks regarding AI liability are continuously underway, with the European Commission recently having withdrawn its proposal for an AI liability directive (Sasdelli, 2025), continuous efforts are necessary in this regard, and for now leaving a gap.

Keeping the human in the loop to take any crucial decisions in such high-risk environments as the nuclear energy is still the best option to prevent big damages. While routine tasks with little risks could certainly be fully conveyed to AI systems. In rather significant decisions it is important to use AI as an assistant only and leave the ultimate decision to the operator, as an AI can hardly be held responsible for its actions. A more thorough framework would be necessary in this regard.

4.6.7 Ageing

The extended lifetime, whilst in principle positive, can also have negative aspects, which have not been considered before. Extension of lifetime certainly has positive economic aspects, but considerations such as knowledge preservation or the non-replaceability of certain components are of crucial importance (Nuclear Energy Agency, 2006). If NPPs reach lifetimes of 60 years (Nuclear Energy Agency, 2006), this has drastic effects on the management of the plant, as no human operator will be in the workforce for so long, hence their expert knowledge 'leaving' as well, once they retire. It is hence crucial to provide appropriate and enhanced training of personnel to continue ensure the safe operation of the plants.

It is also possible that certain ageing mechanisms need to be considered, which did not need to be evaluated for the shorter lifetime. During the extended life of the plant, new technologies will constantly emerge, which could render the existing power plants obsolete as they might not be competitive anymore, with the newer plants being magnitudes more efficient and safer.

4.6.8 Energy Requirements

Finally, also the energy requirements of AI should be considered. Paradoxically, as energy generation, like NPPs can make use of AI systems, the AI is also dependent on steady energy supply. With big data, stored in data centres, these require large amounts of energy. An increase of nuclear energy supply for data centres is projected from 2030, particularly through SMRs. (IEA, 2025)

Expansion of data centres, and continuous digitalisation also lead to an increase in electrification. Artificial intelligence is dependent on data centres, hence resulting in a loop and synergy between AI and the nuclear energy sector.

4.7 Future Research Directions and Recommendations

First and foremost, research and methodological development are required to make sure AI decisions and behaviours meet human standards. To ensure this, it is important, that efforts in creating regulations exist. Such regulations also have to keep up with advancements in the field and respond accordingly (Cha, 2024).

As demonstrated, there exists an urgent need for a regulatory framework regarding ethics. Guidelines in this field are necessary to ensure the prosperous continuous innovation, development and application of AI within multiple industries, including the nuclear industry. The decision-making of AI should be examined critically, and the governance should encourage responsible AI use. (Aldoseri et al., 2024)

If AI incorporates human values; such as ethics, the environment or socio-cultural aspects, it can be considered as more useful. Human-centred AI is an approach to AI based on the human contexts, in order to ensure ‘trustworthy AI’. In order to increase transparency, the integration of explainable AI is crucial when it comes to nuclear energy applications. (Mosqueira-Rey et al., 2023)

Enhancing transparency of neural networks can be achieved through using ‘fuzzy logic’. This concept includes ‘partially true’ as a possible outcome and does not limit the system to binary values. This represents human logic better and can help the interpretation process. Further, fuzzy logic is dynamic and can be refined when needed, additionally improving control. (Phillips-Wren, 2012)

Additionally, policies or regulations are needed for promoting AI that can be trusted across various applications in different sectors. Setting standards and benchmarks is a good start to tackling some of the aforementioned challenges (Liang et al., 2022). Validation, licensing and adherence to safety regulations are necessary for the integration of AI into NPPs. In this regard, collaboration between experts of various fields is crucial, to provide adequate guidelines. (Ejigu et al., 2024)

According to Dixon as cited by Cha (2024), there exists a need for regulation of AI, on a global scale, ensuring AI development that is safe. The EU is the first to work on and provide such legislation, which was passed in 2023. To foster innovative prosperity while regulating for protection, collaboration is necessary between governments and companies, based on research and civil engagement (Ejigu et al., 2024).

The regulatory approach regarding AI in this field needs to be flexible and updated, as AI is evolving continuously (Cha, 2024). Collaboration is necessary, between experts from the AI domain as well as from the nuclear field (Ejigu et al., 2024).

Regarding the issue with subgoal setting, which is the main mechanism of AI, regulations are needed for its operation to be more transparent and ultimately safer. It is widely recognised that a profound understanding of AI's decisions can help tackle risks. As AI is implemented to enhance safety and security within NPPs, human supervision is needed to ensure safety of AI mechanisms. (Cha, 2024)

In an attempt to minimise problems arising in the future, Nay and Daily (2022) as cited by Cha (2024) recommend testing and using simulations in order to forecast the behaviour of AI, this can result in a reduction of side effects of AI on humans and the environment.

Training of personnel is also fundamental when it comes to addressing the challenges of implementing AI within nuclear operations (Ejigu et al., 2024). For a successful incorporation of AI within the nuclear field, it is important that researchers continuously improve AI models to meet the high safety requirements of O&M systems (Huang et al., 2023).

The challenge of explainability and transparency mentioned earlier can be mitigated through so-called 'explainable AI' (XAI). When designing AI, the algorithms should be able to explain their results. Solving a problem effectively is not enough, reasoning to how and why a certain result was chosen is crucial to eliminate 'trust issues' and ensure higher value AI systems. XAI can be attainted through algorithmic transparency. (Mosqueira-Rey et al., 2023)

XAI increases not only trustworthiness and confidence in the model but also the informativeness which support the decision-making processes. Interactivity is also inherent to XAI, where the human-machine interaction is what guarantees success. Mosqueira-Rey et al. (2023) underscore the importance of interactivity between humans and AI. They label it as "*Human-in-the-loop machine learning (HITL-ML)*" and group together active learning, interactive ML and machine teaching. In active learning humans are supporting the machine if necessary only, in interactive ML a more collaborative approach prevails, where active continuous communication guides the process. In machine teaching the human expert is still in full control of the learning process.

Although the integration of AI into nuclear systems for enhanced safety has shown to be promising, additional effort is necessary. Primarily in ensuring that the AI is reliable, which it can only be if it is explainable. Further, ensuring high data quality is one of the most important tasks when aiming to provide reliable AI. Investments need to be made, to possibly include AI systems to enhance already-existing NPPs and not only reactors to be deployed in the future. Regulatory efforts are certainly necessary in ensuring safe nuclear power plants. Future research should focus on countermeasures to overcome current challenges

Another problem was the data issue, seeing as AI systems are reliant on data input. To counteract this problem, and since data on NPPs is limited, due to it being a high-risk sector, it is necessary to enhance data, to be able to enhance safety. A knowledge database, containing broad information on incidents at NPPs around the world, can help train AI models and enhance their accuracy. Seeing as in the field of nuclear energy it is difficult to create experiments and observe real-time emergency reaction results.

Furthermore, it is important, that robust regulatory frameworks exist and are being brought forward in the next years. AI can help in the regulation-drafting process as well as in analysing the compliance of NPPs with certain guidelines, leading to licensing of safer NPPs.

The aspects laid out throughout the thesis were critically assessed and lead to various recommendations on how gaps and challenges may be overcome, and the full potential of AI may be used.

The main arguments for using AI within the field of nuclear safety, are related to efficiency and effectiveness of safety tasks or measures. AI mimics human behaviour, but without the negative traits of fatigue or oversight because of distraction, hence eliminating human error. AI is able to make use of big data which the human operator simply cannot do. Through the shift towards decision-making that is observation-based, operations become more accurate and safer.

While the enhanced efficiency, reduced costs, higher reliability and consistency, and the scale at which AI can operate are all arguments for its adoption to improve safety, a few aspects need to be considered. AI should not completely replace the human operator in critical decision and needs supervision.

For this purpose, a conceptual design was built for the implementation of AI within a nuclear power plant (see Figure 3). The AI can assist the operator, by making sense of big data from various sensors, radars and other sensors of the nuclear power plant. The AI system then analyses this input and takes a decision conferring it to the human operator. Through the integration of a 'surveillant', second AI system, which needs to overlook the decision-making of the first AI and report back to the operator, higher safety can be supported. This can ensure a second safety layer and help with the transparency issue. The human operator is kept in the loop at all times and is responsible for final decision, based on the first AI's outcome recommendation and the second AI's analysis. Using natural language processing can further support the interaction between the AI system and the human operator and enhance transparency and explainability.

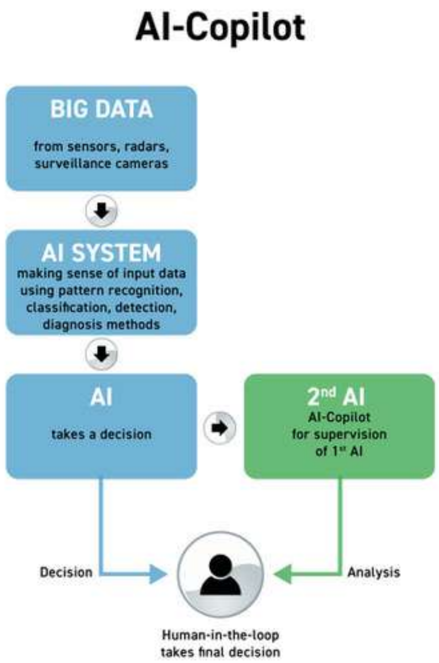

Figure 3: Recommended AI integration into NPPs (own work)

To summarise the recommendations and future steps, a list of necessary measures has been created:

1. *Creation of a regulatory framework on the integration of AI within the nuclear sector, to ensure standardised safety guidelines*
2. *Centres of excellence for AI integration into industries*
3. *An international organisation focusing on AI within the nuclear sector, such as the IAEA and Euratom but focusing on all 3S, as more cooperation is needed in this regard*
4. *Digital twins of NPPs using AI*
5. *AI as an assistant, keeping the human-in-the-loop*
6. *Ensuring explainable AI, by setting guidelines on algorithmic transparency as well as using supervisory AI*
7. *Collective open-source database containing historical and real-time data of NPPs for training of AI systems and research purposes*
8. *Mock-up facility for experimental and training purposes*

The potential outcomes of integrating the recommended steps, would be enhanced safety, increased synergy of the 3s, advancements in research due to higher international cooperation and a robust regulatory framework.

5. Summary and Conclusion

The aim of this research, was to demonstrate AI's potential in enhancing safety of nuclear power plants using a more holistic approach, bringing together all existing and possible future safety enhancing technological AI advancements and considering synergies to other fields.

The study has shown that various AI methods can in fact be used for enhancing safety at NPPs, through predictive maintenance, decision-making support, anomaly detection, fault-diagnosis and emergency response. While there was a lot of existing research on various of these fields, it is important to note that the thesis was limited by the lack of real-world applications.

Integrating artificial intelligence into nuclear power plants, to enhance the safety, has to be carefully considered. Whilst complete autonomy of AI in running the plants cannot be the solution, incorporating AI in the form of a virtual assistant for operators seems to be feasible, as it frees up time of the worker for other important tasks and facilitates the access to relevant information (ANS, 2023).

Pattern recognition and its respective interpretation has been identified as one of the most important and effective AI applications within monitoring of radiation and fault detection.

While not directly linked to enhanced safety, another possible application of AI technologies within NPPs that was found, is for energy optimisation, to reduce any energy going to waste. Also, regulatory compliance may be achieved quicker through the adoption of AI methods.

The intertwining of AI and operators is crucial, humans should collaborate with AI by using it as a decision-making support agent and assistant and AI at the same time may learn from operators, for future automated decisions.

Intelligent agents have a promising applicability in decision-making processes. There has been ongoing research about intertwining humans and systems to have them synergically learn from each other. It is imperative that these agents communicate, coordinate and are human-centric to ensure that autonomous AI systems can be trusted. (Phillips-Wren, 2012)

As discussed under the challenges, the extended lifetime might be problematic, when it comes to competitiveness in the market. In order to not put NPPs with an extended lifetime at a disadvantage, it is important to consider methods for integrating emerging technologies and AI systems in already existing reactors. AI possesses great potential in the preservation and continuous development of knowledge across vast amounts of data over decades. Unlike humans, AI systems have the ability to store and learn from both previously learned and newly acquired information indefinitely, unlike humans whose expertise may be lost due to retirement or mortality. AI could hence serve as a continuously present support agent, assisting operators and newly employed less-skilled personnel.

Taking into account the continuous development and emergence of new technologies and systems, particularly in the field of AI, it is evident that useful discoveries are happening at all times. AI could certainly also support research and maybe discover something new autonomously. But more importantly, it is necessary to assess how, possibly groundbreaking technological advancements can be integrated into NPPs once they are already commissioned. Future research should focus on such challenges, in order to continuously improve safety of NPPs.

With the aim of creating highly reliable AI, a key factor which was identified was the data. For reliable AI, high quality of data is crucial. Open-source access to any available historical data concerning past failures and other incidents that AI could learn from would be important and harmonisation in this regard is crucial, in order to make data comparable and useful in enhancing safety at NPPs in the future. While some IAEA databases exist, the lack of collaboration in this regard, slows current or future breakthroughs.

Training AI with the highest quality and most broad amount of information is fundamental in rendering AI systems as efficient and as reliable as possible and enhancing safety through the integration of these tools. High quality data made available and accessible can only be attained through strong collaboration efforts.

Collaboration is equally important in the 3S concept. As demonstrated, various technologies for safeguarding purposes which can be enhanced through AI technologies, are also very viable in enhancing safety at NPPs.

Further, to ensure trustworthy AI, it is equally important, that AI systems' decisions be rendered explainable and eliminate the 'black box' dilemma. Algorithmic transparency has been identified as a viable solution. What could also be considered is adding another AI systems which surveys the primary AI systems in its decisions and could help explain why the system has come up with a specific solution. While this does not ensure complete safety, it is nevertheless and added layer, aiming at increasing transparency, and ensuring no risky decisions are being taken autonomously by the primary AI.

The concept of redundancy is hereby translated into AI applicability; a redundant AI system providing the necessary extra layer of safety and performing when the primary fails to perform correctly and makes a mistake. The double-checking through two AI systems, can enhance safety at NPPs even more than one alone. Of course, this could become an endless chain of AI systems surveying each other, which then becomes inefficient again, but considering at least one or two 'redundant AI's' could be a game-changer.

As Thomas Hansueli Zurbuchen, former associate administrator at NASA (National Aeronautics and Space Administration), mentioned in an interview, he needs experts on his side, who tell him 'No', hence he specifically employed someone to say 'no' when he is wrong about something (Wegner & Amend, 2022). The importance of review and re-evaluation is underlined. Acknowledging that humans make mistakes is one step, acknowledging that artificially intelligent systems, which are made to 'enhance human capabilities' may also make mistakes is equally important. Human errors can be eliminated through the implementation of AI, but mistakes made by AI shall also be avoided.

AI is very promising in supporting NPP operations and its integration within the design of new as well as already existing plants should be considered. AI applications can predict failures bound to happen before they occur and can hence support decision-making of operators. It would be beneficial to include speech recognition and permit closer interaction between the operators and the system. Semi-autonomous NPP operations could be a solution, as long as humans are kept in the loop for critical decisions, which require ethical consideration for example.

Hybrid implementation of AI for increased safety during O&M of NPPs, along with human supervision of the AI to keep humans in the loop and have them intervene, when necessary, can help "*[maximize] AI functionalities while minimizing societal risks*" (Cha, 2024).

While there are various challenges which may pose some hurdles for the full implementation of AI within the nuclear field, these can and should be addressed. The scope of this thesis focused on safety, but security and safeguard issues are equally important. With AI integration, particularly cybersecurity risks become a more important issue and should be further researched.

The limitations of this thesis are not only the scope of the thesis but also the limited real-time data and research on the topic. AI applications within the field are still at an early stage of deployment and mainly hypothetical application was assessed. It is important to consider other fields than the nuclear sector, where applications of AI might be more advanced, in order to assess real-life potential.

Overall, AI is able to substantially reduce human time and effort, radiation exposure and downtime of NPPs, through the application of various technologies demonstrated in this thesis. By early detection of anomalies, AI offers the opportunity of responding in a timelier manner and resolve arising issues effectively. AI can optimise processes and enhance safety at nuclear power plants, but its real-life applications must be further explored.

Some questions arising from the thesis, are whether AI will replace the human being and to what extent. Can it completely replace humans or where should the limit be? While the thesis focuses on the enhancement of safety in nuclear power plants, these questions are important to consider for various fields where AI applications are discussed.

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List of Tables

List of Figures