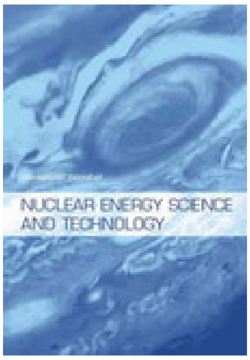

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A review on environmental management for nuclear power plant sites

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A review on environmental management for nuclear power plant sites

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Abstract: Site management of a Nuclear Power Plant (NPP) encompasses the entire site suitability planning process, considering physical and social aspects, community acceptance, nuclear waste management and decommissioning. This research constitutes a Systematic Literature Review (SLR) synthesising prior studies concerning NPP site management strategies. We employed five databases named Scopus, DOAJ, Euro PMC, EBSCO and ProQuest for 2014 to 2023. Among 1594 titles, 16 published articles were identified for meta-analysis using the PRISMA framework. The findings indicate the existence of prerequisites that must be satisfied before NPP siting, including environmental suitability, resilience against natural disasters and consideration of social aspects such as settlements. Public engagement in the siting process is crucial for effectively managing NPPs, contributing to attaining clean and sustainable energy goals. Furthermore, a specialised strategy is imperative for NPP management to ensure adherence to security and safety protocols while preventing adverse impacts on the surrounding environment and facilitating nuclear decommissioning. Despite challenges like nuclear uncertainty from political factors and radioactive waste concerns, NPP presents a viable energy option for mitigating global climate change.

Keywords: energy management; green energy; nuclear.

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1 Introduction

Managing a Nuclear Power Plant (NPP) site is a complex undertaking, encompassing multiple stages of careful consideration and adherence to environmental safety and security protocols (Pavlakovič, 2022). The initial crucial step involves identifying locations abundant in radioactive elements, which serve as the power source. Moreover, selecting an appropriate site for a NPP entails comprehensively evaluating various facets of the physical and social environment (Susiati et al., 2022a). This phase is the most delicate and arduous, given its intricacy in securing public endorsement for NPP construction within their living environment (Sugiawan and Managi, 2019). The focus extends beyond merely ensuring the inhabitants' safety during NPP operations; what holds more importance is assigning the authorities the duty of implementing all nuclear safety procedures (Lee et al., 2022).

One crucial aspect of NPP management is effectively handling radioactive waste. It holds immense significance as the waste's impact on the surrounding environment during NPP decommissioning is considerable. The management of radioactive waste presents a formidable challenge due to its inherent hazards to human health and the environment (Apted and Ahn, 2017).

Stringent protocols are essential for effectively managing nuclear waste and preventing ecosystem contamination. Adequate technology and infrastructure are crucial for handling radioactive waste efficiently, ensuring environmental protection and human well-being (Mohsen and Abdel-Rahman, 2021; Holdsworth et al., 2023). Managing a nuclear power plant site requires a delicate balance between security, environmental sustainability and public acceptance (Almeida et al., 2020).

Overall, nuclear energy is regarded as a promising alternative for addressing climate change, primarily due to the abundant availability of uranium (Naghi et al., 2023). Advancements in nuclear technology and supportive policies further bolster the case for adopting atomic energy. However, the implementation of nuclear energy is confronted with substantial challenges. The primary hurdles centre around public acceptance of NPP development and apprehensions regarding safety and environmental risks. Furthermore, elevated operational costs and the looming threat of natural disasters also present formidable barriers to NPP operations (Shi et al., 2018; Zhu et al., 2016). Consequently, the crucial need for efficient communication among governments, the nuclear sector and the general public cannot be overstated. Thoughtful examination of financial elements and the rigorous implementation of security measures are integral elements in responsible nuclear energy administration.

Bhattacharyya and Khalid (2021) conducted several Systematic Literature Review (SLR) studies on NPP management, specifically focusing on nuclear project assessments. These studies highlighted that each type of nuclear power has both opportunities and challenges regarding climate change adaptation. A similar endeavour was undertaken by Yang et al. (2022), who emphasised that nuclear development necessitates careful consideration of various factors, including potential threats from disasters, technological aspects, nuclear safety, energy policy and stakeholder behaviour. However, it is essential to note that prior research still exhibits several limitations, particularly in its scope and comprehensiveness. Many studies have addressed only specific facets of the broader subject. In light of these gaps, there is a growing need for more recent SLR studies about NPP management strategies. Such studies are crucial in aiding policymaking and facilitating informed long-term decision-making. This research encompasses intricate aspects, from identifying suitable locations for NPP development stages to addressing public acceptance, radioactive waste management and deactivation processes, as well as from exploring opportunities, challenges, disadvantages, advantages to potential threats.

2 Methodology

This study employs the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) model for conducting a Systematic Literature Review (SLR). PRISMA comprises a set of guidelines designed to enhance the quality and transparency of systematic reviews and meta-analyses (Solórzano et al., 2022). An SLR is a rigorous research approach involving a meticulous and methodical search for pertinent studies, followed by a critical assessment and synthesising their findings (Pati and Lorusso, 2018). PRISMA offers a structured methodology for conducting SLRs, encompassing directives for devising search strategies, selecting studies, extracting data and synthesising information (Nurbayani et al., 2022). The articles considered for this research must have been published between 2014 and 2023. This pursuit is based on a keyword index employed within a carefully curated online database. It is worth noting that systematic reviews are confined to research articles that have undergone review and published in English-language journals.

2.1 Identification

This stage entails the exploration of scientific articles within online research databases, namely Scopus, DOAJ, Euro PMC, EBSCO and ProQuest. The choice of these platforms is informed by several factors, including accessibility, time coverage, thematic pertinence and content quality (Wesz et al., 2023). We utilise diverse scientific databases in our attempt to extensively search for high-quality articles. Moreover, this study considers the potential for overlap, wherein an article might be catalogued in multiple scientific databases. In order to identify pertinent articles, the research employs specific keywords for the search process, encompassing terms such as NPP, environment, strategy, management, energy transition and climate.

Table 1 Information about the database

Database	*URL*	*Provider*
Scopus	https://scopus.com/	Elsevier
DOAJ	https://doaj.org	Infrastructure Services for Open Access
Euro PMC	https://europepmc.org/	Europe PMC Funders' Group
EBSCO	http://www.ebsco.com/	EBSCO Industries
ProQuest	https://proquest.com/	Ann-Arbor

2.2 Screening

This step aims to curate the articles collected from the database, following the approach outlined by Ratner et al. (2023). The process involves a comprehensive screening to eliminate potential redundancies from multiple databases and align the articles with the researcher's objectives. Initially, a pool of 1739 articles was compiled from diverse scientific databases. However, this number was refined to 1594 titles following the screening phase. Subsequently, a meticulous evaluation of title relevance ensued, identifying 91 articles with content unrelated to the intended scope. These articles pertained to various power plant types, fell outside the publication window of 2014–2023. Consequently, this stage yielded 110 articles that fulfilled the specified criteria.

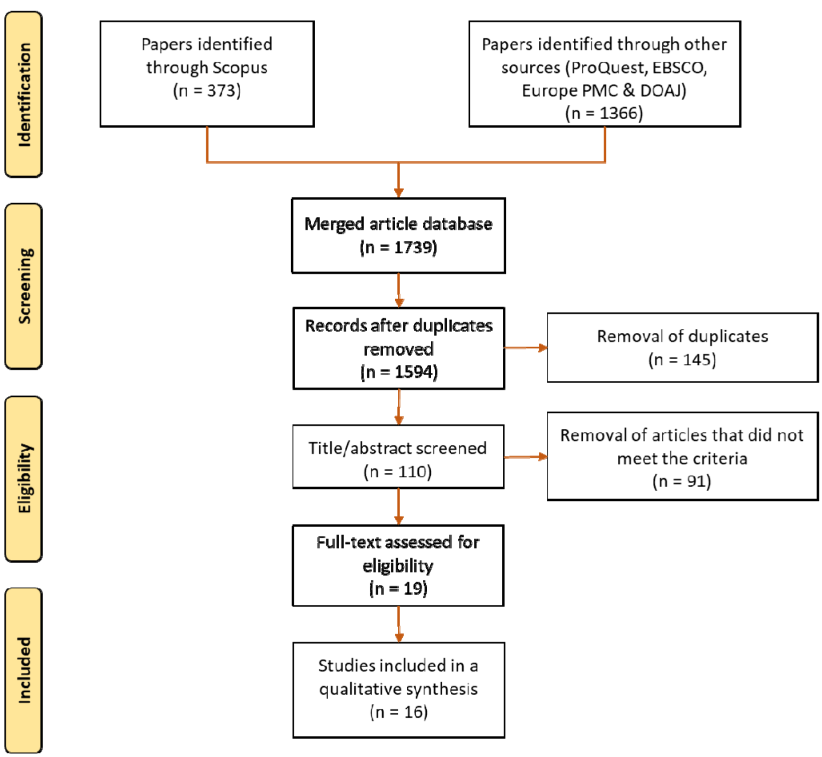
2.3 Eligibility

At this juncture, articles meeting the initial criteria necessitate a thorough validation through comprehensive reading and examination of the complete text. The paramount objective is to ascertain the presence of all requisite sections. This evaluative phase encompasses a meticulous review of the abstract, introduction, methodology, results, discussion and conclusions. Researchers must ensure the seamless integration and coherence of all segments. If any articles are deemed unsuitable, researchers must transparently elucidate the rationale for their exclusion, thereby mitigating potential bias (Tawfik et al., 2019). Articles confined to a narrow spectrum of the NPP management strategy are considered unsuited for inclusion. Consequently, within this stage, 19 articles fulfil the prerequisites to advance to the subsequent phase.

2.4 Included

The articles from the preceding stage underwent a re-selection process to align with the research objectives, specifically for conducting a meta-analysis of environmental management strategies concerning NPP sites. This phase offers an additional advantage by enhancing the efficiency of article content analysis (Mengist et al., 2020). Articles deemed suitable for qualitative synthesis encompass various facets of NPP management, encompassing siting, public participation, radioactive waste management and decommissioning. Conversely, articles that lack these elements are considered unsuitable. Furthermore, the chosen articles must feature NPP management strategies about opportunities, challenges, strengths, weaknesses and threats. Through this sequence of stages, only 16 articles meeting these criteria were identified for further analysis (see Figure 1).

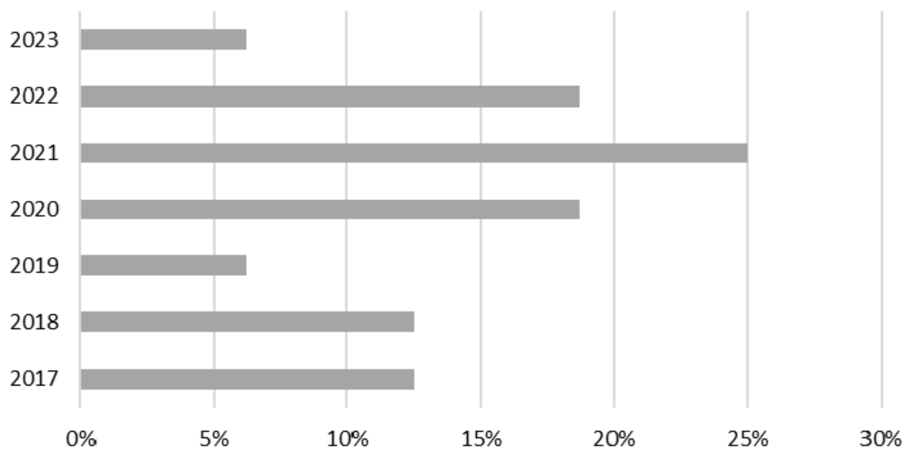
Figure 1 The article selection process commences with identification and concludes with inclusion (see online version for colours)



3 Results

Although the data collection criteria for SLRs were initiated in 2014, the chosen articles fall within the 2017–2023 timeframe, encompassing the most recent six years. These articles impeccably fulfil all criteria stipulated by the author. Before 2017, Geographic Information System (GIS) and remote sensing held prominence, yet their integration with decision-making methods were limited, resulting in numerous studies omitting details regarding the process of selecting suitable locations for NPP sites (Widiawaty, 2019; Susiati et al., 2022b; Dede et al., 2023a). In contrast, contemporary circumstances reflect a global shift towards exploring alternative energy sources due to depleting fossil fuels and the influence of geopolitical dynamics (Bazilian et al., 2019; Vakulchuk et al., 2020). This trend is reinforced by the advent of diverse decision-making methodologies, including artificial intelligence and machine learning (Dede et al., 2022). The accompanying diagram illustrates this evolution (see Figure 2).

Figure 2 Percentage of published articles from 2017 to early 2023



3.1 Environmental criteria for NPP management

When determining a suitable location for constructing a NPP, thoroughly considering geological factors is paramount (Abdullah et al., 2023). These geological elements impact the nuclear facility's construction and influence the designated area designated for nuclear waste management. Additionally, selecting a secure site, resilient against natural disasters like floods, landslides, earthquakes and tsunamis, assumes considerable significance (Katona, 2019). This rationale is underscored by past events that have jeopardised safety, causing casualties, extensive damage, and trauma. The earthquake and subsequent tsunami in Fukushima, Japan, in 2011 is a stark example, resulting in harm to the nuclear reactor cooling system and subsequent radiation leaks (Fukasawa et al., 2023). This event initiated a discussion about the safety and potential risks associated with nuclear energy, leading to an increased focus on nuclear management, particularly in the realm of site security, as part of efforts to minimise and address these concerns (see Table 2).

Table 2 The primary criteria for NPP sites

Main criteria	*Sources*
Geological and geomorphological conditions	(Rodríguez-Penalonga and Moratilla-Soria, 2017; Karim et al., 2018; Siqueira et al., 2019; Bersano et al., 2020; King and Jones, 2020; Lemieux et al., 2020; Gierszewski et al., 2021)
Natural disasters	(Uhunamure et al., 2021)
Environmental impacts	(Serp et al., 2017; Xu et al., 2018; Du et al., 2022; Pathak et al., 2022)
Human population	(Serp et al., 2017; Xu et al., 2018; Bersano et al., 2020; Pathak et al., 2022)
Climate and water resources	(Bersano et al., 2020; Gierszewski et al., 2021)
Infrastructure and electrical grid	(Lemieux et al., 2020)
Land use	(Bersano et al., 2020; Karim et al., 2018; Bhattacharyya and Khalid, 2021; Krūmiņš and Kļaviņš, 2023)
Transportation	(Gierszewski et al., 2021)
Environmental economics (valuation)	(Du et al., 2022)

Additional considerations encompass land suitability, water usage and population density. The availability of ample water and the ease of facilitating its conveyance for reactor cooling are pivotal factors (Khattak et al., 2017). The chosen development site must be distanced from residential areas, safeguarding the surrounding physical environment. Beyond the physical and social environmental facets such as land and geology, proximity to critical infrastructures like renewable power plants, mining operations or oil and gas facilities is also considered. For instance, a study conducted in Latvia concluded that the country's attributes, including its potential for energy independence and low-carbon energy generation, render it suitable for constructing NPPs (Krūmiņš and Kļaviņš, 2023). Security is another pivotal criterion in site selection, addressing safety risks, including mechanical malfunctions. Acknowledging that suitability is contingent on the specific nuclear technology employed (Bhattacharyya and Khalid, 2021) is essential.

Upon establishing the suitable location, the subsequent imperative is to secure public acceptance for nuclear programs, encompassing the siting of nuclear waste disposal as well (Roh and Kim, 2022). The four principal entities crucial for ensuring these social measures are: the government, communities, electricity companies and experts within their respective domains (Rodríguez-Penalonga and Moratilla-Soria, 2017; Karim et al., 2018). Consequently, public engagement assumes paramount significance, encompassing the content outlined in Table 3. It entails educating the public about their concerns surrounding nuclear energy and actively involving them in the decision-making process. In numerous nations, a top-down approach is adopted for nuclear waste disposal site selection, which also incorporates community participation in decision-making. The government also promulgates regulations mandating public consultations and the assessment of risks to social stability before initiating a nuclear project, serving as legal instruments (Gierszewski et al., 2021). Public acceptance of nuclear energy remains a crucial concern for policymakers seeking to ensure access to safe and affordable electricity. Diverse methodologies, including quantitative studies, can delineate public participation and the perspectives of experts integrated into the decision-making process (Xu et al., 2018).

Table 3 Community involvement into NPP management

Content	*Sources*
Nuclear technology	(King and Jones, 2020)
Waste management	(King and Jones, 2020; Bhattacharyya and Khalid, 2021; Shin and Lee, 2021)
Concerns about nuclear (perceptions and sentiments)	(Xu et al., 2018; Uhunamure et al., 2021; Du et al., 2022; Yang et al., 2022)
Life cycle assessment (LCA)	(Serp et al., 2017)
NPP site	(Siqueira et al., 2019; Bersano et al., 2020; Krūmiņš and Kļaviņš, 2023)

Table 4 Processing nuclear waste from NPPs

Action	*Sources*
Establishment of a competent organisational committee	(Rodríguez-Penalonga and Moratilla-Soria, 2017; King and Jones, 2020; Uhunamure et al., 2021; Lemieux et al., 2020; Karim et al., 2018; Du et al., 2022)
Sorting and processing of waste based on its level	(Serp et al., 2017; Siqueira et al., 2019; Bersano et al., 2020; Lemieux et al., 2020; Du et al., 2022; Pathak et al., 2022)
Residual heat energy utilisation	(Bhattacharyya and Khalid, 2021)

Effective nuclear waste management stands as an equally pivotal facet within the realm of nuclear technology management. Entities responsible for processing radioactive waste and employing Spent Nuclear Fuel (SNF) technology must meticulously handle waste from NPPs to ensure complete environmental safety (Rodríguez-Penalonga and Moratilla-Soria, 2017). Fostering an awareness of the perils associated with nuclear and radioactive emissions also plays a vital role in waste management practices. The planning process of waste disposal sites entails public participation, often facilitated by establishing committees and appointing responsible individuals drawn from the community (King and Jones, 2020; Uhunamure et al., 2021). Moreover, radioactive waste disposal facilities must be meticulously designed, considering waste classification based on radioactivity type and level (Serp et al., 2017).

In the endeavour to decommission nuclear facilities, the presence of an official institution within the concerned country that oversees operations, decommissioning, remediation and cleanup, adhering to legal mandates, assumes paramount importance (Shin and Lee, 2021). A comprehensive safety risk analysis is conducted during the decommissioning process, encompassing evaluations of decommissioned radioactive sources and the potential environmental ramifications associated with decommissioning nuclear installations (Gierszewski et al., 2021). Meanwhile, the Levelised Cost of Energy (LCOE) methodology is harnessed to compute annual deactivation expenses (Xu et al., 2018). LCOE represents the electricity price required for the project to break even, encompassing all costs, inflation and the opportunity cost of capital (Lorenczik et al., 2020).

The decommissioning process generally entails adherence to NPP management regulations within each project and country (Gierszewski et al., 2021). It commonly involves oversight from management entities and official authorities and can even entail collaboration with other nations (Karim et al., 2018; King and Jones, 2020). This undertaking must align with a legal framework, though suggestions from the community may still be considered, particularly in cases where early decommissioning of NPPs is desired (Shin and Lee, 2021; Du et al., 2022). The government must attend to various aspects associated with the decommissioning cost for each power plant, encompassing expenses related to utilised fuel and site restoration (Siqueira et al., 2019). Furthermore, the decommissioning process differs based on the reactor type, owing to specifications variations.

3.2 NPP management strategy

3.2.1 Opportunities

Nuclear energy holds significant potential for reducing greenhouse gas emissions (Rodríguez-Penalonga and Moratilla-Soria, 2017; Serp et al., 2017; Siqueira et al., 2019). It can contribute to sustainability through minimal greenhouse gas emissions, efficient natural resource utilisation and even carbon neutrality (King and Jones, 2020; Krūmiņš and Kļaviņš, 2023). Additionally, nuclear energy offers other advantages, including fostering economic development, attracting substantial investments, generating employment opportunities and fostering scientific and technological innovation (Bersano et al., 2020; Lemieux et al., 2020). Nuclear energy can be a primary subject for enhancing public participation in deliberative decision-making about national strategic policies (Shin and Lee, 2021). Furthermore, nuclear energy indicates a country's progress and facilitates foreign cooperation to meet neighbouring countries' electricity demands (Uhunamure et al., 2021). Nuclear energy is relatively more lucrative than alternative sources like hydropower and solar power plants, which demand vast land areas (Karim et al., 2018). As an energy source capable of generating high calorific values, NPPs introduce new possibilities for transitioning from fossil fuel-heavy cogeneration to a renewable energy-dependent paradigm (Bhattacharyya and Khalid, 2021; Gierszewski et al., 2021; Yang et al., 2022). Consequently, nuclear energy is prioritised in addressing energy crises, mitigating air pollution and curtailing point sources of global climate change (Xu et al., 2018; Mathew, 2022; Pathak et al., 2022).

3.2.2 Strength

Notable advancements in nuclear technology have transpired, particularly in nuclear fuel enrichment, radioactive waste management and energy recycling, instilling greater confidence in their safety (Rodríguez-Penalonga and Moratilla-Soria, 2017; Siqueira et al., 2019; Bersano et al., 2020; King and Jones, 2020). It represents a pivotal driver propelling nuclear energy's evolution, extending to the stage of technology export, especially for those nations endowed with uranium fuel reserves and supported by skilled human resources (Xu et al., 2018; Yang et al., 2022). Numerous countries have now advanced nuclear fuel cycle processing technologies, often in tandem with other carbon-free energy sources like wind, solar and biomass (Serp et al., 2017; Rehm, 2023). Establishing a dedicated organisation responsible for nuclear waste management and the availability of technology for radioactive waste management constitute pivotal measures in optimising nuclear energy utilisation (Uhunamure et al., 2021; Shin and Lee, 2021; Du et al., 2022).

Countries like Bangladesh and Poland serve as exemplars, aspiring to develop nuclear technology as a cornerstone of their low-emission energy systems, aiming for complete energy management independence (localisation) (Karim et al., 2018; Gierszewski et al., 2021). Efforts to integrate nuclear power with other renewables within clean energy technologies are intensifying. India, meanwhile, boasts significant experience and expertise in the nuclear domain, with up to 95% of equipment and components produced domestically (Pathak et al., 2022).

3.2.3 Weaknesses

Weaknesses in nuclear energy management manifest both internally and externally. For instance, governmental provision of nuclear waste storage and management facilities has encountered setbacks due to disagreements between central and regional authorities (Rodríguez-Penalonga and Moratilla-Soria, 2017; Shin and Lee, 2021). Furthermore, the substantial initial capital investment and stringent safety regulations contribute to the high cost of nuclear energy (King and Jones, 2020; Du et al., 2022; Yang et al., 2022). The protracted duration of NPP construction, spanning tens of years, amplifies expenses, strains human resource capabilities and elevates the risks of construction and licensing delays (Xu et al., 2018; Uhunamure et al., 2021). Political stability is pivotal in enticing investors to engage in NPP ventures, even as financing efficiency evolves with technological progress (Siqueira et al., 2019; Bersano et al., 2020; Nam et al., 2021). Additional vulnerabilities encompass limited economies of scale, challenges in reducing dependence on fossil fuels and delays in nuclear technology development within developing nations (Karim et al., 2018).

3.2.4 Threats

Nuclear energy confronts threats stemming from various factors, primarily attributed to natural disasters and technical malfunctions (King and Jones, 2020; Du et al., 2022). Natural calamities like earthquakes and tsunamis can potentially damage nuclear reactors (Ishola et al., 2019; Siqueira et al., 2019; Lemieux et al., 2020). Moreover, the impact of extreme weather also necessitates vigilant consideration (Bersano et al., 2020). Technical failures are intricately linked with apprehensions about potential nuclear accidents, adequacy of reactor coolant, radiation dispersion, permeable boundaries and the long-term disposal of radioactive waste, all of which amplify concerns within NPP operations (Rodríguez-Penalonga and Moratilla-Soria, 2017; Karim et al., 2018; Xu et al., 2018; Bhattacharyya and Khalid, 2021; Gierszewski et al., 2021; Uhunamure et al., 2021; Pathak et al, 2022; Yang et al., 2022).

3.3 Challenges in NPP management

Adopting nuclear energy through NPP as a substitute for fossil fuels encounters various hurdles that necessitate resolution (Serp et al., 2017). Uncertainty surrounding the future trajectory of nuclear energy, profoundly influenced by political decisions, has prompted certain entities to propose the closure of all NPPs (Rodríguez-Penalonga and and Moratilla-Soria, 2017). It is essential to acknowledge the existence of numerous anti-nuclear organisations and societies that persistently oppose the future utilisation of this energy source (Bersano et al., 2020; Shin and Lee, 2021). While it is undeniable that

NPPs operate more cleanly compared to other energy sources, it should be noted that nuclear energy still yields carbon emissions stemming from mining activities, fuel transportation and waste processing (Krūmiņš and Kļaviņš, 2023). However, decommissioning endeavours are far from straightforward, demanding meticulous planning due to their inherent technical intricacies (King and Jones, 2020). Public apprehension is well-founded, primarily from concerns about radiation release into the surrounding environment in the event of a disaster or technical malfunction (Lemieux et al., 2020). For instance, releasing nuclear waste heat remains a significant concern for farmers residing near NPPs, as it poses a potential risk to their crops (Bhattacharyya and Khalid, 2021).

These phenomena present a challenge in attracting investors, particularly when securing international funding for long-term NPP projects is demanding. This task includes persuading political adversaries and the general public (Siqueira et al., 2019; Uhunamure et al., 2021; Yang et al., 2022). The utilisation of NPPs as an energy source necessitates enhancements to the electrical grid to expedite the transition process and achieve energy diversification (structural change) in pursuit of the Net Zero Emissions (NZE) target (Gierszewski et al., 2021; Pathak et al., 2022).

Another challenge entails ensuring effective regulation and the availability of proficient personnel and experts in nuclear energy management, all while contending with adverse public perceptions (Karim et al., 2018; Krūmiņš and Kļaviņš, 2023). In nations that lack a history of nuclear energy reliance, the presence of adept human resources for essential technologies in waste management and fuel reprocessing remains scarce (Xu et al., 2018). Ultimately, to confront safety challenges and propel nuclear technology development, diverse application scenarios, waste treatment approaches and system advancements must align with legal frameworks, thereby mitigating or minimising various social risks (Du et al., 2022).

4 Discussion

The criteria for NPP management primarily centre around environmental conditions, acting as a pivotal determinant of reactor operational sustainability. Safety takes precedence, emphasising location's vital role (Farmer, 2012; Grimston et al., 2014; Openshaw, 2019; Susiati et al., 2022c). Factors include disaster preparedness, cooling sources, population density, land usage rights and local climate. Numerous uncontrollable elements contribute to comprehending the risks of selecting a reactor site. NPP developers increasingly consider integrating existing power systems, reactor management methodologies and environmental assessments during operation (Ho and Kristiansen, 2019).

Currently, criteria for NPP siting often lack a comprehensive assessment of public perception, particularly within the vicinity of potential project sites (Kristiansen, 2017; Ho et al., 2019; Wang et al., 2019). Navigating the management of NPP sites poses a challenge for countries newly embarking on nuclear energy as an electricity source. An approach utilising Life Cycle Assessment (LCA), as highlighted by Serp et al. (2017), presents a precise option to mitigate risk. LCA encompasses a facility's entire industrial and lifecycle, from construction to demolition and ultimate waste management (Zafrilla et al., 2014; Alwaeli and Mannheim, 2022). From a regulatory standpoint, careful consideration must be given to site and infrastructure preparation, shaping public opinion, human resource development and waste management.

Numerous challenges arise from the social, economic and political contexts influencing NPP developments in each country; specific projects are constrained by conflicts of interest, leading to apparent stagnation. Involving the public through a top-down mechanism accompanied by meticulous polling is the optimal approach for planning nuclear reactor decommissioning. Several countries have effectively operated research reactors as Small Modular Reactors (SMRs), with public acceptance relatively secure as regulators can demonstrate the project's dependability (Vujić et al., 2012; Rowinski et al., 2015; Budnitz et al., 2018). Coordinating between the government and NPP management must be executed cautiously to minimise disparities in actions arising from policy misalignment.

Regarding nuclear waste disposal, the choice of materials is pivotal to attaining operational efficiency and effective environmental impact management (low-level waste, high-level waste, intermediate-level waste) (Corkhill and Hyatt, 2018; Siqueira et al., 2019). Highly radioactive materials necessitate storage within geologically stable formations (Laverov et al., 2016; Lemieux et al., 2020; De Vicente et al., 2022). Therefore, the selection of partners for nuclear energy development must be predicated on their performance, portfolio and reliability.

The development of NPPs differs from other power plants, as lapses in management are not always discernible to the public (Dede et al., 2020; Widiawaty et al., 2020). Discipline is the primary key; safeguarding individuals and the environment against radiation exposure must be coupled with preventive measures (Sehgal, 2011). Consequently, protocols for identifying and managing operational malfunctions and environmental repercussions constitute responsible nuclear energy usage. Transparency becomes a managerial obligation toward the community (Kim et al., 2013; Schreurs, 2014; Chung and Lee, 2017). Power plant authorities ensure the absence of grave miscommunication that could potentially compromise operations and human safety. Radiation control can adopt a socioeconomic approach, considering ecosystem goods and services surrounding reactors, whether influenced by force majeure or operational glitches (Zagrebaev and Trifonenkov, 2017; Dede et al., 2023b). Spreading awareness about these risks is not intended as intimidation but rather fosters comprehension and collaboration to uphold the sustainability of NPPs.

Nuclear energy is a strategic undertaking, and the assertion that a country's ability to operate independent NPPs implies a potential to produce atomic weapons is not entirely unfounded; as a result, these projects are inherently tied to global interests (Jasanoff and Kim, 2009; Bromet, 2014; Yang et al., 2023). Many argue that nuclear technology is an integral component of sustainable development; NPPs can foster human resource advancement and create avenues for energy exploitation concurrently with other sectors, such as agriculture, healthcare, security and food processing (Du et al., 2022). The preparation of human resources and nuclear specialists necessitates education from elementary to high-school levels. Establishing programs in higher education institutions or vocational high schools is an apparent requisite, given the scarcity of schools directly offering nuclear programs (Susiati et al., 2023). It is essential to recognise the requirement for strong backing to present nuclear energy as an environmentally friendly and sustainable source, working in conjunction with other renewable energies, to meet both national and global objectives for energy transformation (Bhattacharyya and Khalid, 2021).

5 Conclusion

Our systematic Literature Review (SLR) delves into the site management strategies of NPPs, drawing data from multiple databases spanning 2014–2023; however, only 16 articles satisfied the criteria for analysis. Effective measures in energy management are imperative, encompassing factors such as ensuring an ample supply of cooling water for reactors, local infrastructure readiness, appropriate land usage, population density and related facilities, all while safeguarding against potential disasters. Public participation is equally vital to ensure social stability, enabling the public to securely experience the benefits of nuclear energy. Prudent NPP management must encompass various aspects, including handling Spent Nuclear Fuel (SNF). It is crucial to establish facilities for storing radioactive waste, precluding any negative environmental implications. Thorough planning is essential when approaching the decommissioning phase of reactors reaching the end of their operational lifespan. Nuclear energy presents itself as a viable alternative for reducing greenhouse gas emissions, fostering economic growth through job creation and encouraging social innovation. Technological advancements in nuclear energy provide additional support for these benefits. However, nuclear energy is not without its vulnerabilities and challenges, including political complexities, high costs, potential accidents and issues related to waste management and societal concerns. Addressing these challenges effectively requires systematic efforts in nuclear power plant management, resolution of differing perspectives, strengthening regulatory frameworks and developing skilled human resources.

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