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MORALITY BEFORE KNOWLEDGE

Prospects for nuclear power plant development in Indonesia: A DPSIR framework analysis for sustainable energy transition, economic implications, and environmental considerations

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ABSTRACT

Background: Coal-fired power plants have historically dominated Indonesia's power sector. Using fossil fuels (coal, oil, and gas) is recognized as the most significant contributor to greenhouse gas (GHG) emissions that cause the climate crisis. **Methods:** Therefore, this paper examines the possibility of developing a nuclear power plant in Indonesia by conducting a systematic literature review for relevant references and adopting the DPSIR (Driving Force – Pressure – State – Impact – Response) framework. **Findings:** The result shows that nuclear power applications could be more attractive than the development of other renewable energy sources (wind, solar) in the future because of the non-intermittent low-carbon technology with large output and longer operating life. Besides technical issues, understanding public opinion is essential for creating effective nuclear energy policies. This study emphasizes the crucial factor for Indonesia's future nuclear energy development. The successful implementation of Indonesia's climate action strategy through nuclear power will be enabled by developing collaboration between stakeholders (government, local communities, researchers, and corporate partners) and creating opportunities for international cooperation. **Conclusion:** The threat posed by global climate change has attracted attention worldwide, including Indonesia. Under Indonesia's ambitious decarbonization target and the issue of energy security, adopting nuclear power in Indonesia's electricity system is considered a significant effort for sustainability in the energy transition in the future. **Novelty/originality of this article:** The novelty of this research lies in the systematic approach in analyzing the potential development of nuclear power plants (PLTN) in Indonesia using the DPSIR framework (Driving Force - Pressure - State - Impact - Response).

KEYWORDS: climate change; DPSIR framework; energy security; nuclear power; power sector; sustainability.

1. Introduction

Coal has historically dominated Indonesia's electrical supply. Until December 2022, the energy mix for the power system in Indonesia depends on coal-fired power plants (67%), followed by gas (17%), renewable energy (13%), and oil (3%) (PLN, 2021). The lower production costs for coal-fired power plants have been a significant factor driving up demand for coal. The low price is because the determination of electricity production cost from coal is based only on monetary costs and does not include externalities. The external

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expenses correlated with human health effects. When the externalities costs are excluded, the net present value and the internal rate of return are significantly higher, and the payback time is also shorter (Rokhmawati et al., 2023). The utilization of fossil fuel (coal, oil, gas) power plants in the long term threaten sustainability goals due to their adverse impact on global warming, human health, and energy security (Algarni et al., 2023). Sustainability refers to the capability of both the planet's natural's and human cultural systems to survive and adapt to changing environmental conditions throughout exceptionally long periods.

Due to abundant natural resources, nuclear energy remains a low priority among energy alternatives in Indonesia. Nuclear power must be implemented in Indonesia to improve the environment to promote sustainable development (Cho et al., 2021). Utilization of nuclear energy enhances environmental quality by reducing the ecological footprint ensuring ecological sustainability over a long period (Zhang et al., 2023). Indonesia has been planning nuclear power plant (NPP) construction for about 40 years to respond the future energy security challenges and meet carbon emission targets by considering two prospective sites, namely Serpong, and Bangka Island. Serpong is more feasible than Bangka Island regarding ease of licensing and public acceptance, but Serpong is only prepared for the construction of a small-capacity NPP (experimental power reactor). One of the main challenges in constructing NPP in Bangka Island is related to public perception (Wisnubroto et al., 2023).

The challenges for applying nuclear in each country may be different. Compared to the technical aspect, non-technical factors mainly cause difficulties in developing nuclear power. To improve Malaysia's energy targets, the government has committed to putting effort into human resource development, effective public communication, strengthening current energy laws and regulations, and regulatory body involvement. The research related to public perception, public communication, and stakeholder engagement is part of the strategy for the development nuclear power program in Malaysia (Jaafar et al., 2017). The main issues in several nations that have used nuclear power relate to communication between the government and the public on the one hand and the nuclear industry on the other. Considerations regarding the ability of nuclear power to provide a stable electricity supply, job creation, and no air pollution, can significantly affect public acceptance. In contrast, since the Fukushima nuclear accident in 2011, concerns about nuclear safety, radioactive pollution, and radioactive waste management problems generally cause public disapproval and become new obstacles to developing sustainable nuclear energy worldwide (Edwards et al., 2019). The knowledge level about nuclear energy and exposure to social media potentially influence the individuals' perceptions (for better or worse) (Perez et al., 2020).

The conflict between Ukraine and Russia has significantly increased the attention of various European countries to reduce their dependence on energy imports, including French (Aunedi et al., 2023). France's long-term experience adopting nuclear power has been considered a success story. According to data from the World Nuclear Association, nuclear power was France's primary source of electricity generation (69%). In 2021, France has 56 nuclear reactors with a total production capacity of 61 Giga Watt electricity (Gwe). The development of nuclear energy in France began in 1948 with the installation of the 150 kW ZOE (EL-1) reactor. Nevertheless, French only has a limited resource of uranium; therefore, Velasquez et al. (2020) studied two options of a fuel cycle for NPP, namely closed fuel cycle (CFC) and open fuel cycle (OFC). The result indicates that the CFC method is the best option in order to keep the nuclear reactors working since CFC can conserve uranium by millions of tons (Velasquez et al., 2020). The success of the French nuclear project seems to be influenced by the level of public trust in the state as the decision maker (Lehtonen et al., 2020).

Limiting carbon emissions will require a major transformation in the energy system. Therefore, Nuclear energy will be crucial to lowering GHG emissions and ensuring energy security because it is more stable than renewable energies like wind and solar (Mahmood et al., 2020). EIA's data (2020) showed that thirty-three countries have operated nuclear power. Nuclear energy contributes 10.1% of the total global electricity production. The top

five nuclear power-producing countries are the United States, French, China, Russia, and South Korea (EIA, 2022) (Table 1).

Table 1. World nuclear status, 2020

Country	Total annual electricity production (in billion kWh)	Share of nuclear power generation (%)
United States	789.8	19.5
French	379.5	68.5
China	366.3	4.8
Russia	215.7	21.0
South Korea	152.3	27.7

(Adapted from EIA (2022))

Few studies evaluated the possibility of nuclear power development in several countries using various methods. Agyekum et al. (2020) assessed the viability of nuclear energy as a substitute for other energy sources in Ghana with the SWOT analytical tool by investigating the strengths, weaknesses, and possible opportunities and challenges the project could face. This study was conducted by collecting data from interviews, documents, and existing publications on nuclear energy projects worldwide (Agyekum et al., 2020). Ishola et al. also applied SWOT analysis in assessing Nigeria's readiness for the development of nuclear energy. This study conducted interviews with some energy research specialists to discuss the risk factors associated with safety of nuclear energy (Ishola et al., 2019). Abdullah et al. evaluated the suitability of nuclear NPP sites in Indonesia using the Analytical Hierarchy Process (AHP) concept (Abdullah et al., 2023). Shadiq et al. (2022) investigated the option to strengthening nuclear development in ten countries by applying the lagrange multiplier bootstrap cointegration method.

The findings indicated that these countries' policymakers should give priority to developing nuclear energy facilities and technology, stimulating international cooperation, encouraging private-public collaboration, expanding research on nuclear energy issues, and raising public acceptance (Sadiq et al., 2022). However, the prospect of NPP adoption in Indonesia also needs to be assessed through the DPSIR framework to clearly understand the role of nuclear energy in Indonesia's decarbonization pathway in the future. Therefore, the purposes of this study include: (i) to identify the possible development of nuclear energy for the power sector in Indonesia, (ii) to analyze challenges facing the nuclear power development based on the lesson learned from two selected locations (Bangka Island, and Jepara), (iii) to analyze the public perspective towards nuclear development, and (iv) assessing the factor affecting nuclear power development In Indonesia based on DPSIR framework.

2. Methods

2.1 Research location

This research focuses on two primary study areas in Indonesia, where NPPs are located (Figure 1). The first study area is Bangka Island, specifically in Sebagin village, Simpang Rimba sub-district, South Bangka Regency, Bangka-Belitung Islands. The geographical coordinates for this location are 2°38'42.2"S 105°53'31.4"E. The second study area is Central Java, specifically in Ujung Lemah Abang, a part of Sawah village, Balong sub-district, Kembang district, Jepara Regency. The nuclear power in this area, known as the Jepara NPP, is at the geographical coordinates of 6°25'40.0"S 110°47'20.0"E. These two study areas offer distinct yet relevant insights into the implementation and potential of nuclear power generation in Indonesia's diverse geographical and demographic settings.

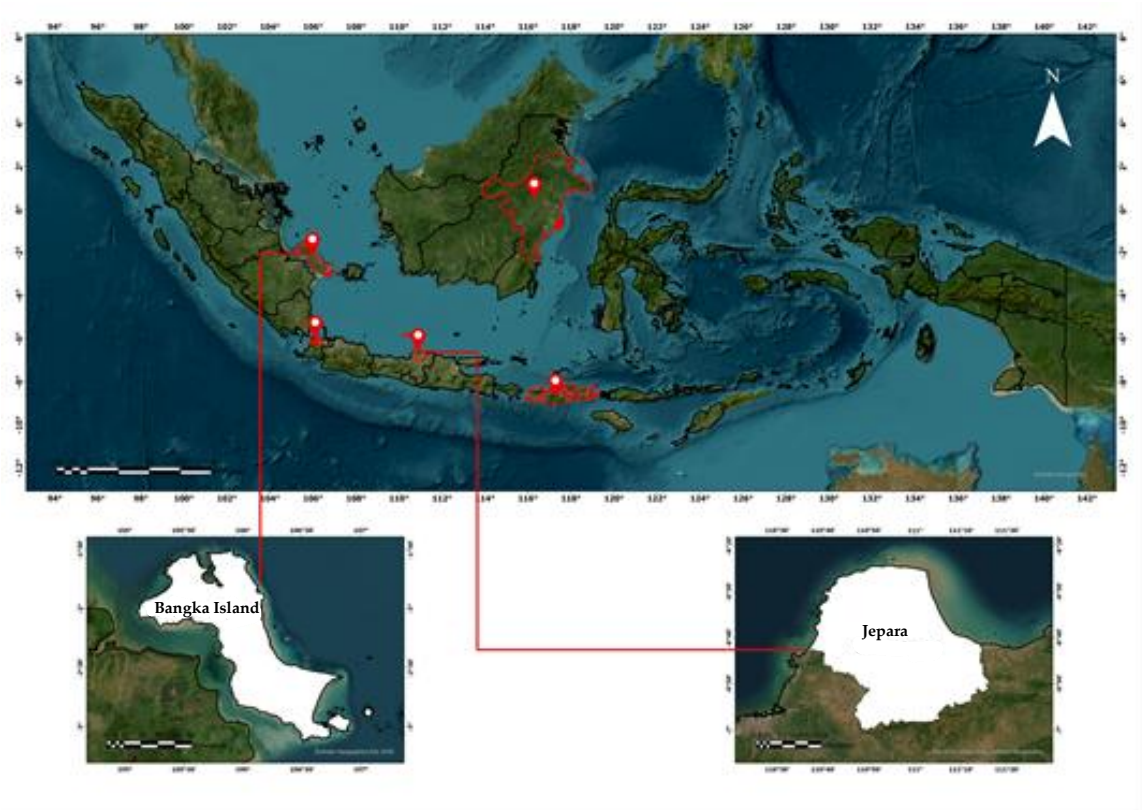

Fig. 1. Study area (Bangka Island and Jepara)

2.2 Research design and data collection

This study uses mixed methods, by utilizing secondary data sources that are qualitative and quantitative. Using a combination of factual data and thematic insights from the (Creswell & Creswell, 2018). As Creswell & Creswell (2018) state, the qualitative method is a research process based on social phenomena and human problems, otherwise, the quantitative method is. This analytical framework thoroughly examines the prospects for developing NPP in Indonesia.

Data collection for this study was accomplished entirely through secondary sources, focusing on two primary categories of data: (i) literature review, and (ii) institution data. To comprehend the worldwide background of NPP, the example of NPP in Fench, and to extract qualitative information on how nuclear energy is perceived in Indonesia, an extensive literature review was carried out. Academic paper and other publications from nuclear power-related groups were all included in the evaluation. To ensure thorough coverage of the subject, the literature review used a systematic methodology (Snyder, 2019). The State Electricity Company (Perusahaan Listrik Negara, PLN), and U.S. Energy Information Administration (U.S. EIA), Ministry of Environmental and Forestry (KLHK) of Indonesia, and International Energy Agency (IEA) provided quantitative information on the electricity generation data.

2.3 Data analysis

In gaining a comprehensive understanding of the role of nuclear energy in Indonesia's power generation landscape, a robust dual approach combining qualitative and quantitative analyzes was adopted in this study. Qualitative data from a complete literature review were dissected systematically using thematic analysis. As Braun & Clarke (2019) defined, this analytical method facilitates the extraction, examination, and interpretation of critical themes embedded in the data. Simultaneously, the application and growth potential of nuclear power for electricity generation in Indonesia was evaluated using descriptive

statistics. The descriptive statistical methodology is essential in summarizing, simplifying, and illustrating data, providing an in-depth picture of nuclear power's current state and future potential in Indonesia (Braun & Clarke, 2019).

2.4 DPSIR framework (driving force – pressure – state – impact – response)

The necessity for comprehensive environmental assessment frameworks is becoming increasingly apparent in the intricate interactions of social-ecological systems (SES), particularly in locations with sophisticated energy ecosystems such as nuclear power. The Organization for Economic Cooperation and Development (OECD) and the European Environment Agency (EEA) initially developed the DPSIR framework, which has been instrumental in the adaptive management of such SESs, specifically in understanding the cause-effect relationships among its five constituents (Gari et al., 2015). This framework has been widely used in analyzing diverse socio-ecological problems caused by human intervention, such as managing groundwater pollution hazards in waste management systems (Mejjad et al., 2021). The insights acquired from DPSIR framework have been valuable in establishing holistic oversight strategies, as demonstrated by attempts to control urban climate change in Jakarta, Indonesia (Kristiadi et al., 2022).

The framework has also been valuable in addressing the exploitation of groundwater resources in areas facing rapid urbanization, like Guwahati City, India (Hazarika & Nitivattananon, 2016). Regardless of its value, several researchers have proposed enhancing the DPSIR framework through integration with other methodologies, emphasizing its ongoing evolution and relevance in addressing environmental and related issues, such as public awareness and practices regarding the harmful effects of pollutants such as PM2.5 (Alzayani & Alsabbagh, 2022). Thus, the application and evolution of the DPSIR framework remain critical to comprehending and dealing with the issues faced by nuclear energy system development and management.

3. Result and Discussion

3.1 Potential development of nuclear power plants in Indonesia

3.1.1 Evaluating the abundance of raw materials for main nuclear resources in Indonesia

This study provides results in the following sections: (i) the potential development of nuclear energy for the power sector in Indonesia, (ii) challenges facing the nuclear power development based on the lesson from two selected locations (Bangka Island, and Jepara), (iii) public perspective towards nuclear development, and (iv) evaluation of nuclear power development in Indonesia based on the DPSIR framework. This section presents factors that support the development of nuclear power (availability of nuclear materials, characteristics, and nuclear energy contribution). Indonesia has significant nuclear energy potential due to its significant uranium and thorium reserves, two important materials for nuclear power generation (KAI Putri et al., 2022).

It is crucial to note that uranium deposits differ in kind, with the sedimentary phosphorus type, also known as the phosphorite type, having the world's greatest resource (Syaeful et al., 2021). Other uranium deposits include black shale, hosted sandstone, and magmatic deposits such as Iron oxide copper gold (IOCG), intrusive, and volcanic. The Organisation for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA) Red Book estimated a global uranium deposit of 5.7 million tons in 2015, dispersed among numerous countries, with Australia leading the pack, followed by Kazakhstan, Russia, Canada, and others (Syaeful et al., 2021). Indonesia also features in this list, hinting at its untapped potential for nuclear energy.

Thorium is another important component in the nuclear power story. It is a radioactive actinide metal with a half-life of 14 billion years that was discovered in 1829. It is estimated that its abundance in the Earth's crust is 3 to 4 times that of uranium (10 ppm against 2.5

ppm). In 2015, 6.3 million tons of thorium deposits were discovered worldwide, spread more equally than uranium. Over 40% of the world's thorium reserves are in Asia, particularly in India, China, and Indonesia (Permana et al., 2021). The National Nuclear Energy Agency (BATAN) has identified and mapped thorium reserves in Indonesia, mostly found in granite associations. These reserves cover many areas, including Bangka-Belitung Island, Kalimantan Island, and Sulawesi Island (KAI Putri et al., 2022).

Uranium and thorium exploration in Indonesia, initiated as early as 1960, has revealed widespread distribution, predominantly in monazite as a by-product of tin and zircon mining. Based on Figure 2, the key regions of interest include West Kalimantan, Central Kalimantan, West Sulawesi, and the tin belt of Bangka-Belitung Island. In West Kalimantan, the Semelangan area showcases a considerable deposit distributed over Pawan, Tulak, and Laur Rivers drainage. In Central Kalimantan, conditions in the Katingan region mirror those in Ketapang, where monazite is also a zircon mining by-product. The islands of Bangka-Belitung lead in unconventional uranium deposits, revealed through limited surface explorations, indicating monazite and xenotime as the main radioactive minerals. Estimated speculative resources in these islands amount to 21,792 tU. Prognosticated resources are also significant in several regions of Bangka-Belitung, such as Bangka Selatan, Bangka Tengah, Pangkalpinang, Tumbang Rusa, and Cerucuk Belitung. Singkep, within the same tin belt as Bangka-Belitung, is projected to contain 1,100 tU of prognosticated uranium resources (KAI Putri et al., 2022; Syaeful et al., 2021). Indonesia's enormous uranium and thorium reserves constitute a tremendous possibility for developing nuclear energy infrastructure. However, effective exploration and management of these resources will be required if their full potential is to be realized.

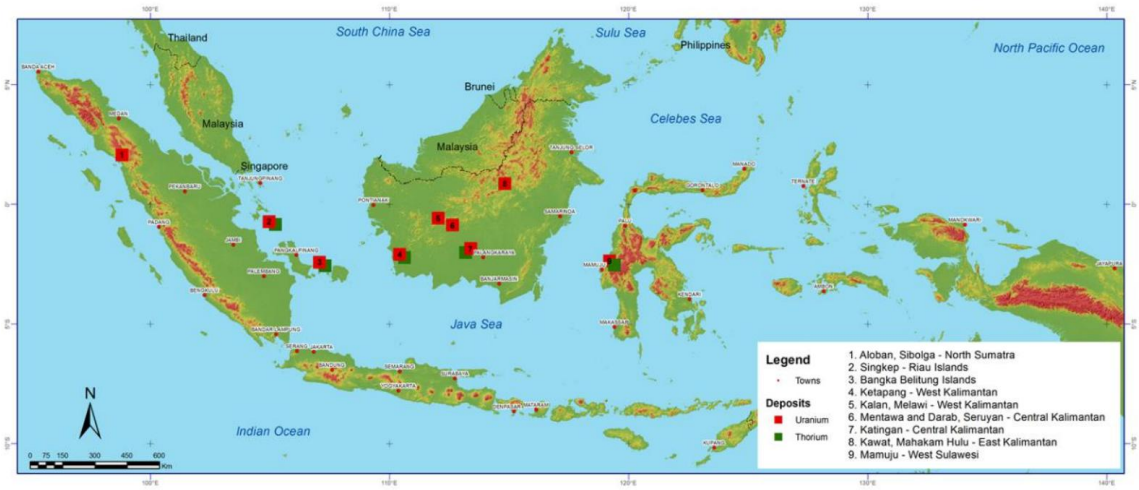

Fig. 2. Distribution of uranium and thorium deposits in Indonesia
(Syaeful et al., 2021)

3.1.2 Nuclear energy as environmentally friendly energy compared to other energy sources

Addressing global climate change necessitates an energy transition towards a low-carbon system, and NPPs present a promising solution in this respect. According to a comprehensive study by Pehl et al. (2017), life-cycle emissions from NPPs are projected to be as low as 3.5–12 gCO2eq kWh−1 by 2050. In stark contrast, the same study estimates that fossil fuel carbon capture and sequestration plants will emit substantially higher levels of greenhouse gases (GHGs) in the 78–110 gCO2eq kWh−1 range. This numerical comparison effectively underscores nuclear power's significantly lower carbon footprint, thereby highlighting its considerable environmental advantages (Pehl et al., 2017).

Moreover, research by Dincer and Acar (2015) affirms the efficiency and capacity of nuclear power. The authors suggest that nuclear power can operate at approximately 90% efficiency, a figure significantly higher than many renewable energy sources. This high operational efficiency, when paired with the capacity to generate large amounts of

electricity, underscores nuclear power's potential as both a robust and environmentally friendly energy solution (Dincer & Acar, 2015). In terms of technology development, nuclear energy is exhibiting promising trends. An analysis of patents by Albino et al. (2014) disclosed an upward trend in patents related to nuclear energy technologies. More specifically, nuclear-related patent submissions rose by an impressive 430% over 25 years, which indicates substantial interest and investment in this sector. This trend testifies to the confidence in and potential growth of nuclear power as a low-carbon energy solution (Albino et al., 2014).

Furthermore, the International Energy Agency (2019) notes that nuclear power significantly contributes to global electricity production, generating 18% of electricity energy in 2018. In advanced countries, nuclear power is the largest low-carbon source of electricity, generating 40% of all low-carbon generation (Figure 3). In particular, nuclear power was responsible for over half the power in French, the Slovak Republic, and Hungary. These data further demonstrate nuclear power's essential role in a global context.

Ram et al. (2018) found that the levelized cost of electricity (LCOE) from nuclear power competes with that of many renewable energy sources, ranging between $50 and $100 per MWh from 2015 to 2030 (Ram et al., 2018). This finding is echoed by a study by Jin and Kim (2018), which found that an increase in nuclear power by 1% reduces carbon dioxide emissions by approximately 2.1%. These data further solidify nuclear power's role in mitigating carbon emissions (Jin & Kim, 2018). The collective body of research strongly advocates for the essential role of nuclear power in crafting a sustainable, low-carbon energy future. This reality is of considerable relevance for Indonesia. Factors such as low lifecycle GHG emissions, exceptional operational efficiency, promising growth prospects, and competitive costs all underscore nuclear power's potential to serve as a sustainable and environmentally friendly energy source. These benefits align well with Indonesia's energy needs and future sustainability goals, making it a fitting choice for the nation's energy future.

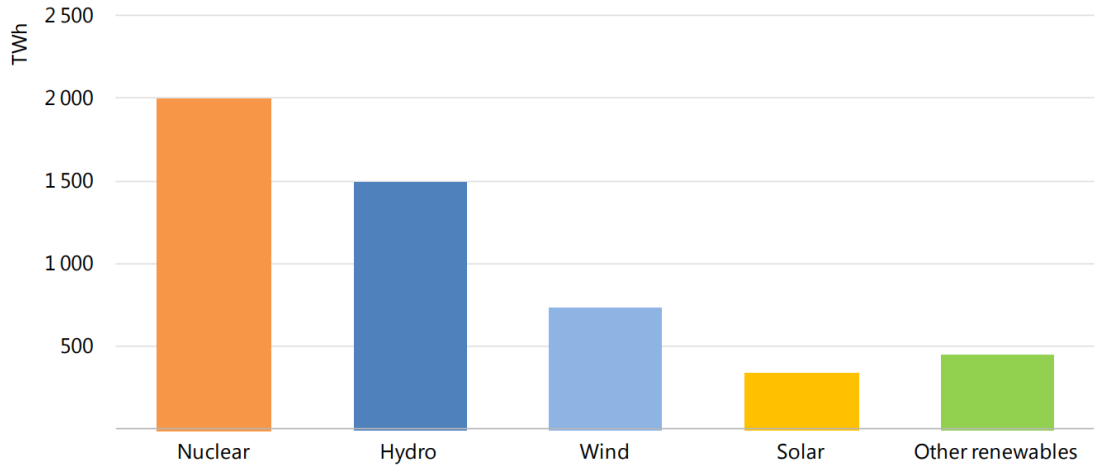

Fig. 3. Electricity generation from low-carbon sources in advanced countries in 2018 (IEA, 2019)

3.1.3 The significant power capacity and baseload capabilities of nuclear power

Nuclear power has proven to be a formidable answer in the quest for reliable baseload electricity sources. Pfenninger and Keirstead (2015) conduct interesting comparative research on the effectiveness of nuclear power as a baseload provider using South Africa as an example. The study shows that, unlike some renewable energy sources such as concentrating solar power, NPPs can deliver continuous electricity generation (baseload) regardless of environmental circumstances such as weather or time of day (Figure 4).

Nuclear reactors' consistent power supply feature emphasizes their vital role in providing energy baseload, especially in locations that demand a stable and resilient power supply infrastructure. Tavoni and van der Zwaan (2011) demonstrate a perspective by

contrasting nuclear power with coal plus carbon capture and storage (CCS) as competing baseload climate control solutions. The study shows that while both can provide large-scale, reliable power, nuclear energy has some advantages. Nuclear power plants can create substantially more electricity than coal with CCS due to their excellent power output. Furthermore, nuclear power is a more environmentally benign option because of its minimal GHG emissions. This validates the concept that nuclear power plants have a vast power capacity and can provide energy baseload with a low environmental impact. (Pfenninger & Keirstead, 2015; Tavoni & van der Zwaan, 2011). Jenkins et al. (2018) showed that the operational costs of nuclear power are substantially lower than those of other energy generation technologies. The study notably emphasized that due to their high-capacity factors and extended service lives (Jenkins et al., 2018). Farfan and Breyer (2017) reported that the average operating age for nuclear power facilities is roughly 30 years, with a projected technical lifespan of about 40 years (Farfan & Breyer, 2017). However, with regular updates and maintenance, nuclear power plants can operate efficiently for extended periods of up to 60 to 80 years (Khatib & Difiglio, 2016). For context, the technical life spans for coal, gas, and oil power plants are approximately 40, 34, and 34 years, respectively. The extended service life of NPPs allows for an extended return on the initial investment, consequently lowering the cost of electricity generated over the plant's operational lifetime.

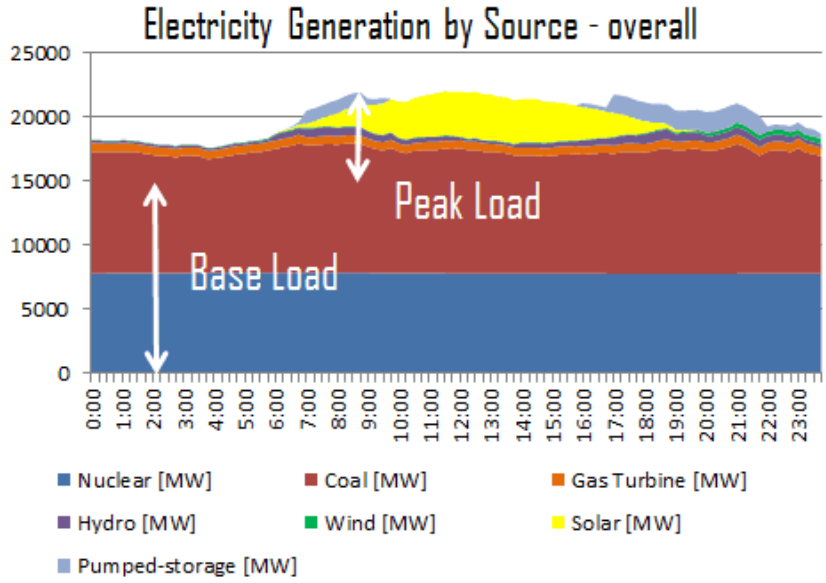

Fig. 4. Baseload capability of nuclear power compared with other sources (Nuclear-Power.com, 2023)

3.2 Challenges facing the nuclear power development based on the lesson from two selected locations (Bangka Island and Jepara)

The previous nuclear accidents (Fukushima, Chernobyl, and Three Mile Island) have raised significant concerns regarding the safety of nuclear energy in various communities, including ASEAN. These countries possibly took a "wait and see" strategy, including Indonesia (Kosai & Yamasue, 2019). Muria (Jepara), Kramatwatu (Banten), Bangka Island, East Kalimantan, and West Nusa Tenggara are some of the places considered locations for nuclear power in Indonesia (see Figure 5). The construction of NPP must consider regulation aspects and the current state to prevent a significant adverse impact on environmental influence (Susiati et al., 2022). In this section, the challenges for the implementation of nuclear energy from two options of prospective locations were discussed, namely, Bangka Island and Jepara, based on the references obtained.

Fig. 5. Research locations for nuclear power in Indonesia

In 2010, The Bangka-Belitung government expressed interest in constructing nuclear power on the Bangka Island. In 2011-2013, BATAN conducted a feasibility study, including investigating the potential sites for the island's radioactive waste disposal. Selecting a disposal site, determining how long radioactive waste, and wasted fuel can be placed in storage before being disposed of, and funding the radioactive waste disposal by waste generators are some of the challenges associated with disposal concerns. The site selection to be used as waste disposal affects the response of the local community (Wisnubroto, Zamroni, et al., 2021). Convincing the public is the main challenge for developing nuclear technology on Bangka Island. Therefore intensive socialization must be addressed (Wisnubroto et al., 2023). Unfortunately, the nuclear power program stopped due to the local province's leadership transition.

Indonesia's experience of research reactors began with the construction of TRIGA Mark II in Bandung at the beginning of the 1960s, followed by the research reactor in Yogyakarta (1979) and Serpong (1987). In 1989, the Government conducted an NPP feasibility evaluation on the Muria, Jepara. The Ujung Lemah Abang region, which is at the tip of the Muria Peninsula, was determined to be the best choice for the nuclear power site at that time, regarding technical and economic considerations (Sugiawan & Managi, 2019). Unfortunately, the plan to build nuclear power in Muria was withdrawn due to the negative acceptance of local society and non-governmental organizations (NGO). The communities are worried about the risks associated with NPP, especially in social and environmental aspects, because the NPP development site is likely to close to Mount Muria, which although not an active volcano, might be at risk of harm (Cho et al., 2021).

3.3 Public perspective towards nuclear power development

With the fourth-biggest population in the world, the need for energy increased significantly at an average annual rate of six percent over the last ten years. Indonesia is projected to promote nuclear power in the document's Long Term Development Plan 2025–2045. Along with this plan, public opinion on the adoption of nuclear power will be crucial to consider, besides economic and technical issues (Yang et al., 2022). People's opinions toward energy technology are based on their overall assessment of the technology's benefits and risks, which is influenced by three variables: individual, psychological, and contextual factors. Sociodemographic elements, including gender, socioeconomic status, and age, impact an individual's characteristics The psychological aspect is influenced by the degree

of confidence, experience with, and degree of knowledge related to technology. While the characteristics of technology, spatial proximity to the energy plants, and public involvement influence the contextual factor. In people's thoughts, benefits and risks are two different ideas that are negatively associated and have an adverse correlation (Devine-Wright, 2007).

Sugiawan & Managi (2019) used multinomial logit and route models to evaluate the public acceptance of nuclear power in Indonesia. This study demonstrates that local governments and nuclear energy regulators are the major forces influencing public opinion in support of nuclear energy. Meanwhile, it is difficult to discern how the central government is pushing the use of nuclear energy (Sugiawan & Managi, 2019). The mechanism of public engagement in Indonesia has not been effective because, despite the fact that more dialogue and information sharing between the authorities and the community were carried out, it tended to have a top-down and one-way (Kosai & Yamasue, 2019). Cooperation between universities, research groups, and state-owned enterprises will be a crucial component in developing nuclear power facilities in the future (Wisnubroto et al., 2021).

Due to the publication regarding public perceptions of nuclear energy development in Indonesia being less discussed, this study presents the lesson learned from other countries in the context of investigating public opinion. Ho et al. (2019), studied public perception in Thailand and Vietnam. The findings showed that to get the people's trust, stakeholders must have a sense of sympathy for the community. In other words, the public expected the institution responsible for managing nuclear power plants to be an expert in nuclear technology, be transparent regarding how technology work, and indicate that the institution has the same concerns as the public. Funding for research and public education about nuclear energy needed to be also increased to encourage the public engagement (Ho et al., 2019). The knowledge about nuclear energy had a significant impact on how individuals perceived risk and profit of nuclear energy. It is necessary to increase knowledge transfer to decrease Generation Z perceives nuclear energy as a risky alternative energy source (Naureen et al., 2020). The participation of all stakeholders when addressing issues regarding the expansion of nuclear power must be created (Choi et al., 2021).

Determination of the location of nuclear energy significantly affects acceptance from the public. The appropriate location for nuclear power projects is outside the boundaries of a town but sufficiently close to the city because the public believes that nuclear power projects open up opportunities for various direct and indirect jobs. A public awareness campaign is also required to determine what the public understands about nuclear power and how much risk they believe (Alzahrani et al., 2023). Bangladesh also prioritizes increasing public awareness of nuclear issues through seminars and campaigns to encourage positive responses from the public (Hosan et al., 2022). However, limiting global warming is not just the government's and researchers' responsibility. Ambitious climate goals require the support and involvement of a variety of societies (Kang et al., 2020).

3.4 Evaluation of nuclear power driver in Indonesia based on the DPSIR framework

The DPSIR framework uses relevant indicators to comprehensively describe a system. The indicators in each category may be related to ecological, social, economic, or governance aspects depending on the topic being investigated, and each category may consider multiple aspects (Brunhara et al., 2023). In this study DPSIR framework, used to investigated the nuclear power driver in category: driver, pressure, state, impact, and response (Figure 6). These are the fundamental socio-economic factors that instigate change or development.

3.4.1 Drivers

In the context of this study, four main drivers have been identified. The first is population growth in Indonesia. With the country's population reaching around 280 million in 2021 (World Bank, 2022), this population trend is increasing, creating increasing energy demand in various sectors such as industrial operations, transportation, and residential use. The increasing demand requires the exploration and utilization of diverse energy sources,

including nuclear power, to ensure energy security (World Energy Council, 2021). The second factor is the intensive use of fossil fuels. Indonesia's energy sector is heavily dependent on fossil fuels, which accounted for more than 80% of the country's energy mix in 2021 (PLN, 2021). This widespread dependence reinforces the urgency for alternative energy sources, including nuclear power. The issue of climate change is a third factor. Indonesia, under its Enhanced Nationally Determined Contribution, has pledged to reduce emissions by 31.89% by 2030 unconditionally and to 43.20% conditionally (Government of the Republic of Indonesia, 2022). This requires a transition from fossil fuels to more sustainable sources, including nuclear energy. The integration of nuclear power could be critical in achieving this environmental commitment (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). The fourth factor is the lack of knowledge about nuclear power. Issues of public acceptance have delayed nuclear power projects in Indonesia. Trust in the managing authorities, especially local governments, and the nuclear energy authorities, is essential to drive acceptance. However, the role of the central government is less clear. Misconceptions about nuclear energy, its benefits, and its risks can greatly shape public opinion and potentially trigger opposition to nuclear power plants (Sugiawan & Managi, 2019).

3.4.2 Pressure

These factors have a direct impact on the environment, driving changes in environmental conditions. Indonesia's rapid population growth and continued economic development are driving a significant increase in energy demand. This increasing demand is putting pressure on existing energy infrastructure and resources. This highlights the urgent need to identify and integrate alternative energy sources, including nuclear power. The integration of nuclear power will contribute to the diversity and resilience of Indonesia's energy mix while addressing the surge in energy demand (IESR, 2021). Energy security and the high demand for fossil fuels are also other concerns. Indonesia's high dependence on fossil fuels exposes the country to potential challenges such as price fluctuations, supply uncertainty, and environmental degradation. Given this context, nuclear power emerges as a strong alternative.

Nuclear power provides a consistent, secure, and locally generated energy supply that can help alleviate the pressures stemming from heavy dependence on fossil fuels (IESR, 2021). Another pressure is the emission reduction target. Indonesia's commitment to reducing greenhouse gas emissions requires the adoption of low-carbon energy sources. Nuclear power, as a low-carbon energy source, can make a significant contribution to achieving these environmental commitments (Government of the Republic of Indonesia, 2022). Poor public perception is also a pressure. Widespread misunderstandings and concerns about nuclear power can put pressure on government agencies and policymakers. This pressure has the potential to make them reluctant to support nuclear power despite its enormous potential benefits, emphasizing the importance of public education and transparent communication about nuclear energy (Sugiawan & Managi, 2019).

3.4.3 States

This aspect summarizes the current state of the environment influenced by the identified drivers and pressures. The first condition concerns the growth of electricity generation in Indonesia. With steady growth in electricity generation in Indonesia, there is a good time to introduce nuclear power into its energy matrix. As reported by the Institute for Essential Services Reform (2022), the energy sector is projected to expand in line with population growth and the country's development measures (IESR, 2021). The extensive dependence on fossil fuels is also highlighted. More than 80% of Indonesia's current energy mix comes from fossil fuels, indicating an unsustainable energy strategy (IESR, 2021). This dependence underscores the urgent need for diversification and the potential integration of nuclear energy. Another important condition to note is the emission reduction commitment:

Indonesia has pledged to reduce greenhouse gas emissions by around 31.89% by 2030. The revised NDC increases the greenhouse gas emission reduction target in the CM1 scenario, the unconditional scenario, from 29% to 31.89%. This emphasizes the need for significant changes in the country's energy mix (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). This transition could involve the integration of nuclear power as a low-carbon energy source. Finally, lessons learned from nuclear projects are important to describe the current state of the environment. The experiences of the Muria Nuclear Power Plant and the Bangka Island Nuclear Power Plant offer important lessons for the future development of nuclear energy (Cho et al., 2021; Wisnubroto et al., 2023).

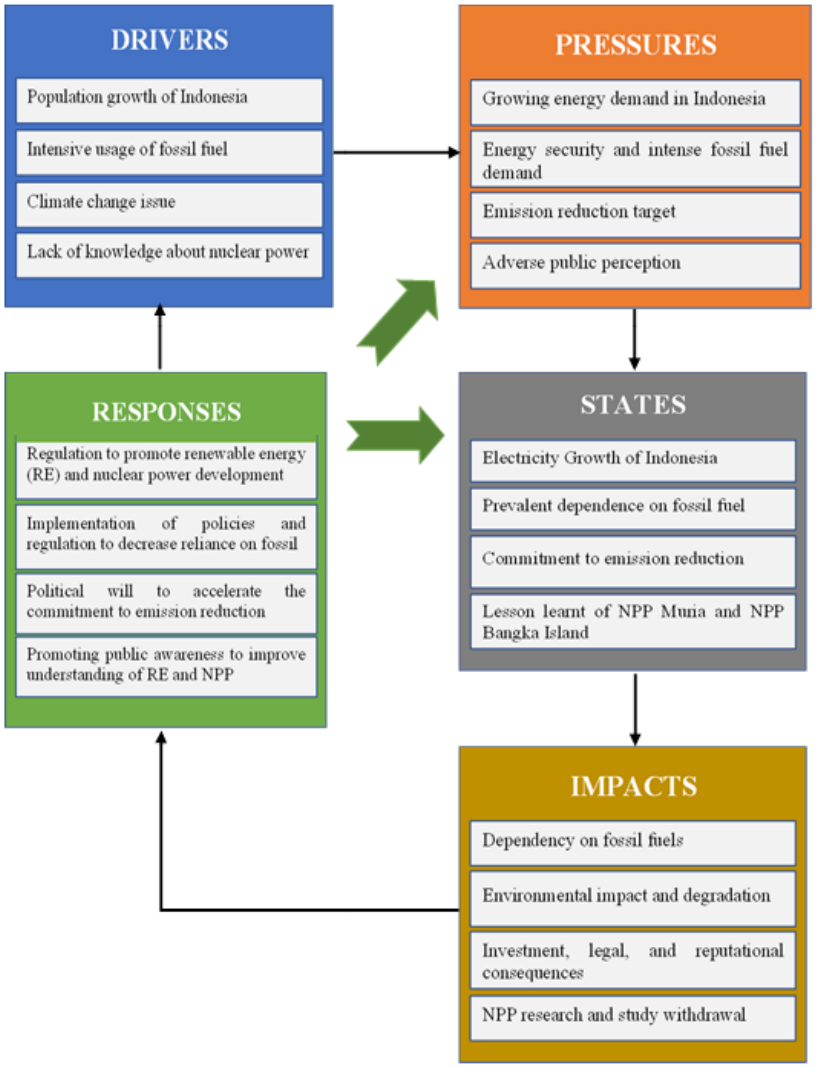

Fig. 6. DPSIR Framework in contect of nuclear energy driver

3.4.4 Impact

This component highlights the potential outcomes or consequences resulting from the pressures placed on the environment. The first consequence is dependence on fossil fuels. Heavy dependence on fossil fuels poses a potential threat to economic and energy stability due to the volatile nature of fossil fuel prices and supply uncertainty (ADB, 2015). With its promise of stable and resilient electricity generation, nuclear energy can act as a stabilizing factor in this scenario. Another consequence is environmental degradation. The surge in industrialization and urbanization in many developing countries, including Indonesia, has led to a substantial increase in anthropogenic greenhouse gas emissions. This scenario contributes significantly to global warming and climate change, triggering a series of environmental crises, including desertification, ocean acidification, and severe weather

conditions. This extensive environmental degradation is often exacerbated by dependence on fossil fuels (Yoro & Daramola, 2020). As a solution, switching to nuclear power can be beneficial because of its much lower carbon emissions, potentially mitigating the worsening impacts of climate change. Indonesia also experiences investment, legal, and reputational consequences. Indonesia's over-reliance on fossil fuels could lead to economic vulnerability, as fossil fuel prices are subject to fluctuations and geopolitical risks. Furthermore, the global trend towards decarbonization and the growing importance of environmental sustainability could influence international investment decisions. Embracing a diverse energy mix with nuclear power could help attract investment, improve the legal framework, and enhance Indonesia's reputation as a responsible and forward-thinking country (IESR, 2021). Another consequence is that the lack of knowledge about nuclear power and negative public perceptions could hinder research and studies related to nuclear power generation. This withdrawal could limit opportunities to develop domestic expertise, hinder technology transfer, and delay the potential benefits that nuclear power can offer, such as clean and reliable energy generation (Sugiawan & Managi, 2019).

3.4.5 Response

This section concerns the actions or measures taken in response to the identified drivers, pressures and impacts to address the underlying issues and promote sustainable development. First, there is a need for regulations to promote renewable energy (RE) and nuclear power development. Implementing a regulatory framework that incentivizes and promotes the development of renewable energy sources, including nuclear power, can drive the transition to a sustainable energy mix. This regulation can provide a clear roadmap for investment, ensure safety standards and simplify the licensing process for nuclear power projects (IESR, 2021). Second, there is a need to implement policies and regulations to reduce dependence on fossil fuels. Enacting policies and regulations that encourage energy diversification and reduce dependence on fossil fuels can facilitate the adoption of nuclear power. This can include measures such as carbon pricing, renewable energy targets and the elimination of subsidies for fossil fuels (IESR, 2021). Third, foster political will to accelerate commitments to reduce emissions. Strong political commitment and leadership are essential to achieving environmental targets. The government needs to prioritize reducing greenhouse gas emissions and allocate resources to support the development and deployment of low-carbon energy sources such as nuclear power (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). Fourth, it is important to raise public awareness to improve understanding of renewable energy and nuclear power: public acceptance and support play an important role in the development of nuclear power projects. It is necessary to implement a comprehensive public awareness campaign, engage stakeholders, address misconceptions, and communicate the benefits and risks associated with renewable energy and nuclear power in a transparent manner (Sugiawan & Managi, 2019). Nuclear power can contribute to meeting energy demand, improving energy security, and sustainable energy goals alongside other renewable energy and technological advances.

4. Conclusion

Developing nuclear power in Indonesia holds great promise for the country's energy future. Given the potential for NPP development in Indonesia, it is critical to address the issues of environmental, technical, economic viability, and societal acceptance. The study of Indonesia's substantial uranium and thorium reserves demonstrates the country's potential as a nuclear energy hub. These resources, if effectively explored and managed, have the potential to contribute to the creation of a long-term and dependable nuclear energy infrastructure. Furthermore, nuclear power has significant environmental advantages compared to other energy sources. NPP can play a critical role in decreasing greenhouse gas emissions and mitigating the consequences of climate change due to their low carbon footprint and great operational efficiency. NPPs' ability to generate huge amounts of

electricity on a continuous basis puts them as a stable baseload power source, which is critical for addressing Indonesia's expanding energy demand. Economically, nuclear power exhibit cost efficiency and long lifespans, allowing them to be financially viable over their operational lifespan. NPP is an economically appealing choice for long-term energy generation because of decreased operational costs and the potential for service life extensions.

Nuclear energy's public perception and comprehension must be adequately communicated, highlighting the benefits while resolving safety concerns. For successful deployment, robust economic planning, funding mechanisms, and the creation of a trained nuclear workforce are required. To ensure the sustainable and responsible use of nuclear energy, rigorous environmental assessments and adequate waste management techniques should be in place.

In brief, the a prospective development of a nuclear power in Indonesia represents a tremendous opportunity for the country's energy sector. Indonesia can diversify its energy mix, cut greenhouse gas emissions, improve energy security, and pave the road for a sustainable and resilient future by utilizing its substantial uranium and thorium reserves and addressing the accompanying problems. A comprehensive approach combining environmental, technical, economic, and social factors, as well as strong stakeholder engagement and dedication to safety and sustainability, will be required for the effective implementation of nuclear power in Indonesia. Despite its importance, this study has limitations. In the future, researchers can conduct an in-depth investigation of public opinion on nuclear power in different parts of Indonesia using primary data collected through detailed surveys and questionnaires.

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The authors was solely responsible for the design and execution of the research, data analysis, interpretation of results, and manuscript preparation.

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