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An Analysis of National Position, Opportunity, and Challenge of Indonesia's Nuclear Program to Support Net-Zero Emissions by 2060

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Abstract: Coal contributed 303 million tons of CO_2 (49% of total emissions) in Indonesia in 2021. The Indonesian government plans to retire all coal-fired power plants (CFPPs) to achieve net-zero emissions by 2060. Nuclear power plants (NPPs) have low CO_2 emissions. This research aims to analyze the status of the nuclear program and examine the opportunities and challenges of NPPs in supporting net-zero emissions. The method used is a literature study of national positions and a simulation of the use of NPPs with the low emissions analysis platform (LEAP) up to 2060. The Business as Usual (BaU) scenario still relies on CFPPs. The retired CFPP scenario consists of NPP utilization of 0%, 5%, 10%, and 15%. It was found that the national position of Indonesia is in phase 1 (considering), because legally there is no policy on the use of NPPs in laws, the National Development Plan, or energy policies. A Nuclear Energy Program Implementation Organization (NEPIO) has not yet been established. The simulation results conclude that with limited renewable energy potential, NPPs have the opportunity to fulfill electricity production needs and reduce CO_2 emissions significantly. The challenge of using NPPs is the increasing production and investment costs of electricity that come along with the increase in the use of NPPs.

Keywords: nuclear power plants; net-zero emission; national position; Indonesia power system; LEAP; CO_2 emission; production cost; investment cost

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1. Introduction

Currently, climate change is one of the major issues faced by many national governments or policymakers as incorporated in the United Nations Framework Convention on Climate Change (UNFCCC). Climate change causes a number of environmental problems, such as rising land temperatures, rising sea levels, melting glaciers, human health problems related to air and water quality, increasing the risk of natural disasters like floods, etc. [1–6]. Climate change is caused by the greenhouse effect, in which solar radiation reaching the Earth will be reflected by the Earth back into the atmosphere, but not all solar radiation will leave the Earth's atmosphere. Some of this solar radiation will be absorbed by greenhouse gases (GHGs) such as CO_2, CH_4, NOx, and fluoride gases. The increase in the concentration of these greenhouse gases in the Earth's atmosphere after the industrial revolution has caused the greenhouse effect and the problem of climate change [4,7,8]. More than 60% of the GHG in the atmosphere is CO_2 from burning fossil fuels, and more than 18% is CH_4 [9,10]. The power generation sector is the main CO_2 emitter, followed by industry, transport, and construction [10–12]. By region, the largest CO_2 emissions come from East Asia (more than 27%), especially China, followed by North America (12%) and Latin America (10%) [9].

Electricity production in the world continues to grow; it increased from 76 thousand TWh in 1975 to 179 thousand TWh in 2022. In 2022, more than 35% of electricity generation came from burning coal, 22% from natural gas, 15% from hydropower, 9% from nuclear power, and the rest came from wind, solar, oil, etc. The contribution of coal to electricity generation has decreased from 38% in 2000 to 35% in 2022. Electricity production by nuclear power plants (NPPs) increased from 2 thousand TWh in 1990 to 2.6 thousand TWh in 2022. However, the contribution of NPPs in the world electricity production fell from 17% in 1990 to 10% in 2022 [13–16]. It has tended to be flat since 2000. The electricity production from NPPs was 2.5 GWh in 2000 and 2.6 GWh in 2022. There was a decline in the electricity production of NPPs in 2011. It was related to the Fukushima Daiichi Accident. The policy of reducing the utilization of NPPs has occurred in Germany since the accident, apart from influential economic and political factors [17–20]. Meanwhile, there has been an increase in the use of renewable energy (RE) such as wind and solar photovoltaics for the past 20 years [13–16]. In 2022, electricity production activity produced 14.65 Gt of CO_2 emissions [10,21]. Indonesia produced more than 619 million tons of CO_2 or 1.67% of the world's CO_2 production in 2021. In terms of energy sources, coal contributes 49%, oil 34%, and natural gas 12% [11]. Electricity production in Indonesia in 2022 was 108 TWh, of which more than 65% came from coal, 17% from natural gas, 7% from hydropower, 5% from geothermal power, and the rest from oil and renewable energies [22]. Indonesia is one of the largest coal-producing countries in the world, with an output of more than 685 million tons of coal up to 2022 (more than 50% exported) [23]. The number of verified coal reserves in Indonesia is about 34 billion tons, so that starting in 2022, the value of reserves to production ratio is over 50 years [24]. With a high value of coal reserves and production, the majority of power plants in Indonesia are coal-fired power plants [25,26]. CO_2 emissions from the power generation industry in Indonesia amounted to 182 million tons of CO_2 equivalent up to 2020 [27].

In an effort to combat climate change, developed countries have committed to adopting the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) to reduce GHG emissions. Emission reductions achieved by a variety of policies with measurable reductions must be periodically reported [28,29]. Indonesia ratified the Kyoto Protocol in 2004 [30]. At the United Nations Climate Change Conference (COP21), the Paris Agreement was reached. Each country lists its efforts to reduce greenhouse gas emissions in its Nationally Determined Contribution (NDC) [31]. Indonesia also ratified the 2016 Paris Agreement [30]. Indonesia's emissions in 2005 were estimated at 1.8 $GtCO_2$ equivalent, with 63% from land conversion and forest fires. Meanwhile, the burning of fossil fuels contributes 19%. In 2016, peat fires (44%) and energy (37%) generated 1457 $GtCO_2$ equivalent. In order to reduce CO_2 emissions, the Indonesian government aims to reduce emissions unconditionally by about 31% [32]. Regarding the power sector, the Indonesian government seeks to increase the use of clean coal technology, reduce the use of coal in the energy mix, and increase the penetration of renewable energy [32,33]. In the long run, net emissions are expected to be zero by 2060.

In the power system, NPPs provide low energy emissions and guarantee energy supply. Renewable energy sources such as hydropower and geothermal energy are strongly influenced by the potential of each region and highly dependent on natural conditions. Other renewable energy sources such as wind and solar have the characteristics of discontinuity related to weather conditions, so there are fluctuations in the supply–demand gap [34–37]. Fossil fuel power generations produce very high GHG emissions. Coal-fired power plants produce 820 gCO_2 equivalent/kWh, and natural gas power generations produce 490 gCO_2 equivalent/kWh. But NPPs have very low emissions, only 12 gCO_2 equivalent/kWh or similar compared to renewable energy. NPPs are one of the energy solutions to the problem of global warming [36,38,39]. To achieve net-zero emissions by 2060, the Indonesian government is also considering the use of NPPs [40]. The Integrated Nuclear Infrastructure Review (INIR) was conducted by the International Atomic Energy Agency (IAEA) in order to evaluate a country's readiness regarding its nuclear program.

The INIR was implemented in Indonesia in 2009 with the conclusion that Indonesia has performed significant preparatory work on most of the infrastructure issues to be able to make a decision to further consider the introduction of nuclear energy [41,42]. The national position is 1 of 19 points of the INIR, which also includes energy policy and energy planning analysis, especially the use of NPPs.

Indonesia is an archipelagic country that has very complicated plate convergences consisting of subduction, collision, back-arc thrusting, and back-arc. Indonesia is located at the intersection of the Indo-Australian, Eurasian, Philippine Sea, and Pacific Plates. This region has a very high level of seismic risk. Since 1900, data have been recorded for 18 major magnitude events ($\geq$M 7.0) per decade. One of the biggest earthquake and tsunami disasters occurred in Aceh in 2004. The earthquake of 9.2 M caused a tsunami and resulted in more than 167 thousand fatalities [43–46]. Indonesia is located on the Pacific Ring of Fire and has 147 volcanoes; 76 of them are active volcanoes and are spread along the islands of Sumatra, Java, Celebes, and Lesser Sunda [47,48]. In terms of natural disaster risks, the development of NPPs in Indonesia is very challenging. The Nuclear Energy Supervisory Agency (Bapeten) is an institution that functions as a supervisor of all activities related to nuclear energy. This is regulated by Law of the Republic of Indonesia number 10 of 1997 concerning nuclear energy. The head of Bapeten issued regulations for the on-site evaluation of nuclear power installations against seismic, volcanic, meteorological, and hydrological risks. This was conducted to mitigate the possibility of natural disasters occurring at NPP installations. Meanwhile, the handling of radioactive waste is regulated by the Republic of Indonesia government regulation number 6 of 2013 concerning radioactive waste management. In this regulation, the National Nuclear Energy Agency of Indonesia (Batan, now incorporated in BRIN) carries out waste management. Through Batan (now BRIN), Indonesia has operated nuclear reactors since 1964. There are three nuclear reactors in Indonesia, namely Triga (2000 kW), which has been operating since 1964 in Bandung, West Java; Kartini (100 KW), which has been operating since 1979 in Yogyakarta; and G.A. Siwabessy (30 MW), which has been in operation since 1987 in Serpong, Banten [49,50]. In general, Indonesia has been operating nuclear reactors safely for the past 50 years. Apart from that, several universities also have nuclear engineering study programs to prepare human resources in this field.

Several studies discussing the use of renewable energy and NPPs in the energy mix for the period of 2050–2060 use the low emissions analysis platform (LEAP). Various scenarios compared to Business as Usual (BaU) have been developed by increasing the use of renewable energy in the power system. These studies find that renewable energy and NPPs can significantly reduce CO_2 emissions in the power system. The reduction in CO_2 emissions affects the increase in investment financing [51–55]. A simulation of Indonesia's energy mix aiming to be carbon neutral by 2050 using TIMES (MARKAL-EFOM integrated system) shows that NPPs and solar photovoltaics are key elements of the energy mix in the future [56]. It is most economical to build NPPs in Southeast Asia (ASEAN) in the context of decarbonization if the immediate costs can be reduced to or equal to the immediate costs of current NPPs in China and Korea [57]. This study aims to analyze the national position of the Indonesian nuclear program, the opportunity of NPPs regarding GHG reduction targets, and the challenges due to cost and safety issues.

2. Materials and Methods

The national position is the result of a strategic formulation process and government commitment to develop, implement, and maintain a safe, secure, and sustainable nuclear power program. The analysis of the national position includes the National Energy Policy and energy planning, implementation of the nuclear energy program, and prefeasibility studies. The Integrated Nuclear Infrastructure Review (INIR) is a comprehensive peer review carried out by the IAEA to assist the nuclear programs of its member countries. This review covers various aspects such as developing a safe, secure, and sustainable nuclear power program. The national position is 1 of 19 points of the INIR. This section includes national commitments related to safety and security, the existence of organizations such as the Nuclear Energy Program Implementation Organization (NEPIO), and national strategies related to the development of nuclear power plants [58,59]. The national position allows political decision-makers to decide whether the nuclear energy program will continue or not.

In this study, a national position analysis is carried out by reviewing Indonesia's energy policies, especially in the electricity sector. This analysis is conducted to analyze Indonesia's position regarding its nuclear energy program. The government's commitment to the nuclear program is reflected in the nuclear policy and the NEPIO's development. The NEPIO structure is analyzed through case studies of the NEPIO structure in several IAEA member countries. In addition, a review of the existing feasibility studies regarding NPPs that have been carried out in Indonesia is conducted to study the results and findings for future nuclear program development.

A seismic, tsunamic, and volcanic risk analysis is carried out to identify candidate NPP location areas. Data on Indonesia's geological conditions, locations of potential seismic hazards, and maps of tsunami and volcanic potential in Indonesia are analyzed to mitigate these risks. Candidate locations for NPPs must have very low risk.

In analyzing the opportunities and challenges of this nuclear program, especially in the economic and emission aspects, a simulation of the utilization of NPPs in the Indonesian electricity system is carried out with the model structure in Figure 1. This simulation uses LEAP software (version 2020.1.0.103) and runs from 2023 to 2060. The year 2022 is the last actual condition (inputting actual data). Coal-fired power plants (CFPPs) are still being built from 2023 to 2030 in relation to the commitments in the RUPTL (National Electricity Plan) [60]. There are two main scenarios that are simulated in the LEAP software, namely the Business as Usual (BaU) scenario and the CFPP retirement scenario. After 2030, the BaU scenario involves continuing to build CFPPs until 2060. The regulations are not limiting of CO_2 emission at CFPPs, or CFPPs can be operated in Indonesia even though producing high the CO_2 emission intensity [61]. Therefore, technologies such as carbon capture are not applied in this scenario, as they are relatively expensive [62,63].

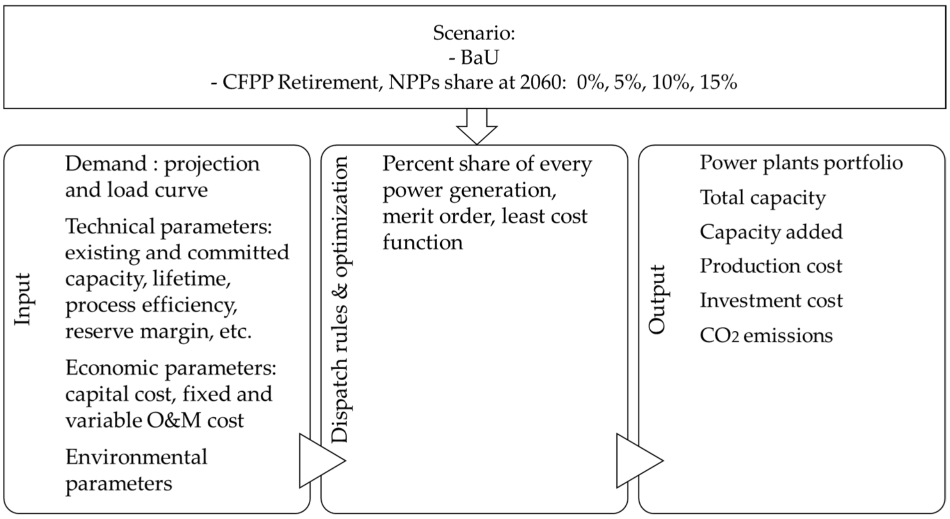

Figure 1. Simulation model (adapted from refs [54–56]).

Meanwhile, the CFPP retirement scenario will stop CFPP construction starting in 2030. In this scenario, the power generations are dominated by hydro, geothermal, and natural gas power plants. The NPPs technology used in this simulation are types of Large Reactors (LRs) and Small Modular Reactors (SMRs). The use of NPPs (LRs and SMRs) is varied at 5%, 10%, and 15% in 2060. The results of the simulation will be compared in terms of the amount of investment and production costs required and the amount of CO_2 emissions produced in the electricity system of every scenario. The detailed assumptions and data of the scenarios are discussed in Section 4.

3. Nuclear Technology and IAEA's Guideline for NPP Development

3.1. Nuclear Power Plant (NPP) Technology Overview

Nuclear energy is the form of energy released by the nucleus of an atom, which is made up of protons and neutrons. This energy source can be produced in two ways: fission (when the nucleus of an atom splits into many parts) or fusion (when the nuclei fuse together). Nuclear energy used in the world today to produce electricity undergoes nuclear fission, while the technology to produce electricity from fusion reactions is in the R&D stage [64]. NPPs are divided into several generations, as shown in the Table 1.

Table 1. Nuclear development.

NPPs	Gen I	Gen II	Gen III	Gen III+	Gen IV	Ref.
Period (years)	1945–1965	1965–1995	1995–2010	2010–2030	2030	[65,66]
Stage	Early prototype reactors	Commercial power reactors	Advanced LWRs	Improved economics	Highly economical, minimal waste	[65]
Type	Shipping port Dresden Magnox	LWR-PWR BWR Candu	ABWR System 80+ AP600			[65]

In terms of generating capacity, there are several types of nuclear reactors, namely Large Reactors (LRs) having up to 700 MWe capacity, medium having a capacity of 300–700 MWe, and Small Modular Reactors (SMRs) with capacity less than 300 MWe [67–70]. Meanwhile, NPP reactors that have a capacity below 30 MWe are called microreactors [71]. There are several types of NPPs depending on the type of reactor coolant (both the coolant's type and the generating steam's method), namely Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), Pressurized Heavy Water Reactors (PHWRs), Graphite Light Water Reactors (LWGRs), Gas-Cooled Reactors (GCRs), Advanced Gas-Cooled Reactors (AGRs), Fast Breeder Reactors (FBRs), and High-Temperature Gas-Cooled Reactors (HTGRs) [68,72]. The differences between the several types of NPPs can be found in Table 2.

Table 2. The different characteristics of the various types of nuclear reactors [73].

Characteristic	PWR	BWR	AGR	PHWR (Candu)	LWGR (RBMK)	FBR
Active core height (m)	4.2	3.7	8.3	5.9	7	1
Active core diameter (m)	3.4	4.7	9.3	6	11.8	3.7
Fuel inventory (tones)	104	134	110	90	192	32
Vessel type	Cylinder	Cylinder	Cylinder	Tubes	Tubes	Cylinder
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	PuO_2/UO_2
Form	Enriched	Enriched	Enriched	Natural	Enriched	-
Coolant	H_2O	H_2O	CO_2	D_2O	H_2O	Sodium
Steam generation	Indirect	Direct	Indirect	Indirect	Direct	Indirect
Moderator	H_2O	H_2O	Graphite	D_2O	Graphite	None

Figure 2 shows that the PWR type accounts for more than 78% of NPPs operating during 2022, followed by BWRs at 11% and PHWRs at 6%. PWRs have several advantages, including ease of use because less electricity is generated as heat rises, that the energy density is high, and that the risk of radioactive waste contamination in the coolant is very low. Since the primary and secondary rings are separated, the water can never be contaminated with radioactive substances in the primary ring of the system [74,75].

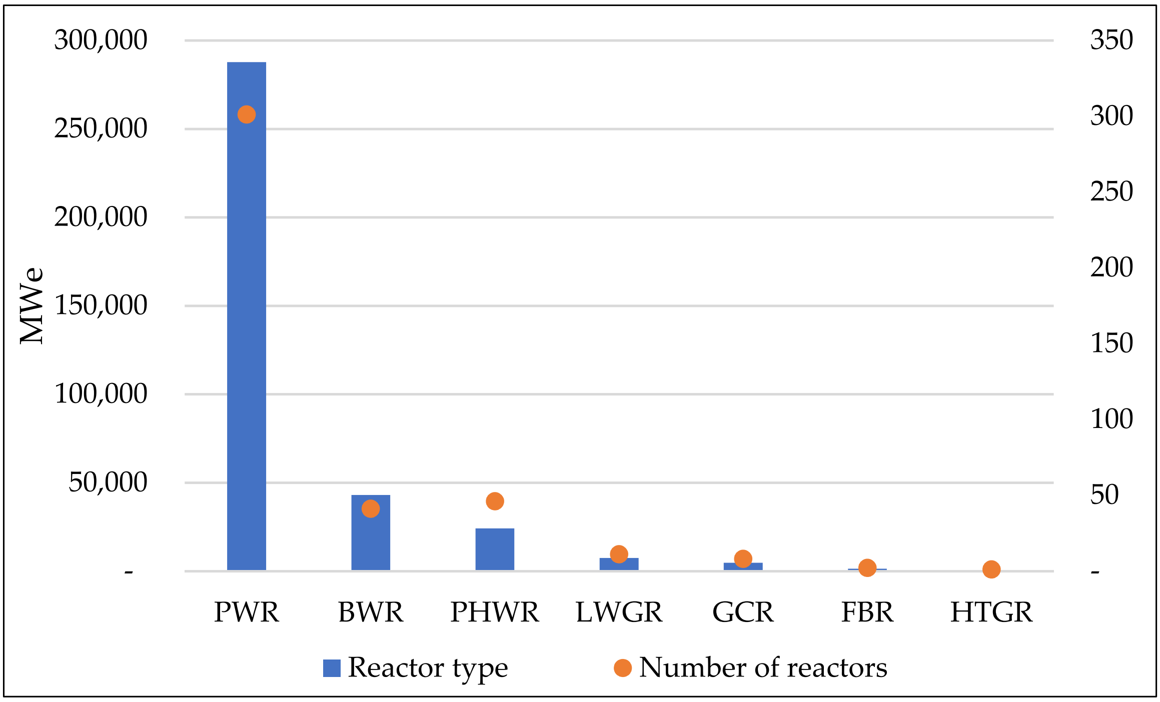

Figure 2. Data on type and number of reactors of NPPs in 2022 (reprinted from [76,77]).

3.2. IAEA Guideline for NPP Program

Regarding designing a nuclear energy program, the IAEA has issued guidelines on the stages that must be completed for the program to be safe and successful. The five stages are shown in Figure 3 [78,79].

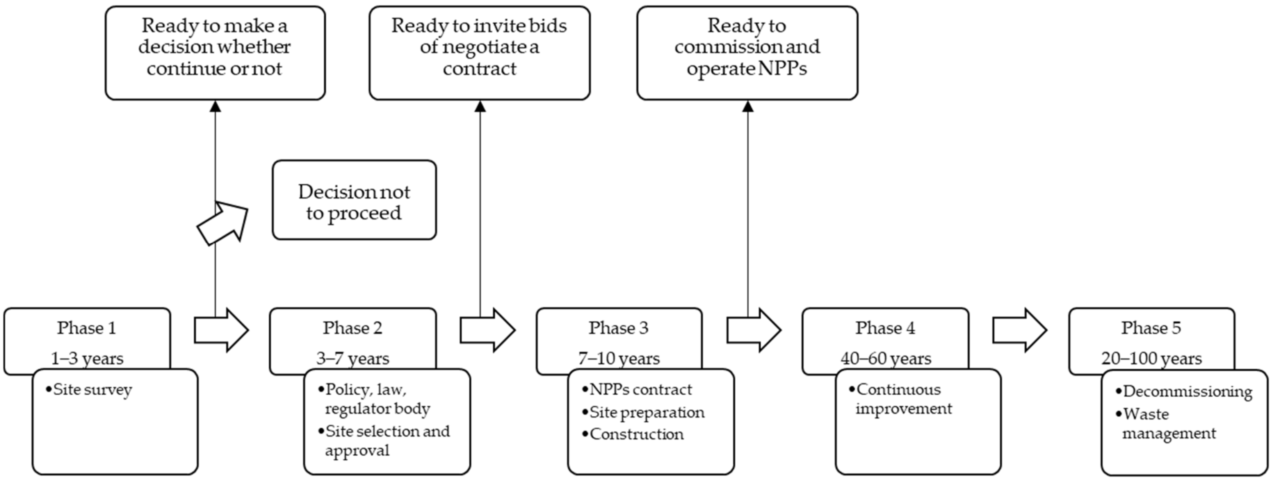

Figure 3. Main phases of safety infrastructure development of NPPs (edited from [78]).

1. Phase 1 comprises security infrastructure considerations to address before making a decision to launch a nuclear power program. This phase is the basis for the nuclear program to operate safely and sustainably through the creation of a legal basis, a nuclear program management agency, and policies on the use of nuclear power. After the reflection period, political decision-makers can decide whether to continue the nuclear program (towards phase 2).

2. Phase 2 involves the preparation of the security infrastructure for the construction of a nuclear power plant after a political decision has been made. This step ensures the safe construction and operation of nuclear power plants in the future. Site assessment and security analysis are conducted in depth.
3. In phase 3, safety infrastructure activities to deploy the first nuclear power plant are implemented to ensure the nuclear power plant can operate safely.
4. In phase 4, safety infrastructure during the operational phase of a nuclear power plant can be achieved through continuous improvement in various aspects, both regulatory and operational.
5. In phase 5, safety infrastructure during the decommissioning and waste management phases of a nuclear power plant is in place to ensure that these phases are safe and do not pose a threat to the environment.

These five stages are the expansion of the previous three general phases (consideration, preparation, and operation). In the first three phases, several steps must be taken to ensure the success of a country's nuclear program (illustrated in Figure 3), namely the decision relating to the nuclear program, the contracting of nuclear power plants, and the operation of nuclear power plants. Following these steps, the usual time for a country to implement a nuclear power for the first time is 10 years [78,80,81].

4. Results and Discussion

4.1. Analysis of National Position

4.1.1. National Energy Policy

Energy policies in Indonesia are based on Indonesian development plans prepared by the National Development Planning Authority (Bappenas) based on the laws in Figure 4. These policies are elaborated in the National Energy Policy (KEN), which is then continued in the National Energy Plan (RUEN). For the power sector, the National Electricity Master Plan (RUKN) and the Power Supply Business Plan (RUPTL) have been approved by the Ministry of Energy and Mineral Resources (MEMR) as reference documents for the development of the future electricity power industry. Regarding nuclear energy, Indonesia has passed a nuclear law (Law No.10/1997). In general, there are several points regarding nuclear energy, as shown below.

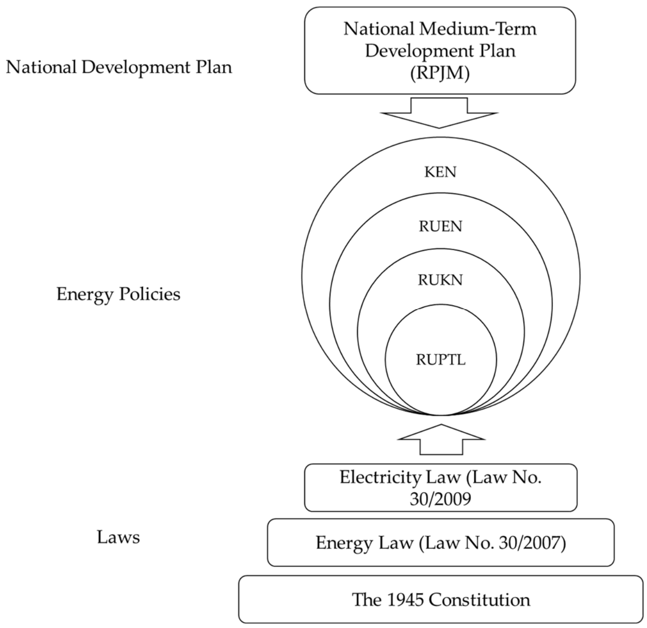

Figure 4. The relationship between laws, energy policies, and National Development Plan [82].

1. The development of a commercial nuclear reactor is decided by the government after consulting with the Council of Representatives of the People's Republic of Indonesia (DPR RI) [83].
2. Nuclear energy is the last resort, taking into account strict safety [33].
3. Operators of nuclear facilities must pay attention to safety and the risk of accidents and must compensate third parties for damage caused by nuclear accidents [33].

The Indonesian government through the MEMR issued documents related to the National Electricity Plan (RUKN), where the latest documents for the 2019–2038 period contain the national electricity policy, the direction of developing electricity supply, the current condition of the electricity supply, and the projected electricity demand for the next 20 years [84]. The RUKN is made with several basic assumptions, such as the growth of electricity energy by 6.8%/year with a target of the role of renewable energy by 23% in 2025 and 28% in 2038. However, the use of NPPs in the RUKN is not listed. The Electricity Supply Business Plan (RUPTL) 2021–2030 initiated by PT. PLN (Persero, the state-owned electricity company of Indonesia) and approved by MEMR is made for a planning period of 10 years. The plan includes commitments related to the construction of new power plants, transmission lines, and distribution lines. In the document, NPPs are also not projected in the national electricity system [60].

4.1.2. The NEPIO Established

In the process of building nuclear infrastructure, there are three important groups involved, namely government, regulatory agencies, and owner/operators, which can be public or private. Regulators should be independent, separate from government agencies, and may have the authority and financial resources to ensure that decisions taken can be independent (if not, they might be affected by the pressures of political, economic, and social conditions). To carry out its nuclear program, the government must establish a high-level working body or committee tasked with coordinating the nuclear program among the stakeholders and reporting to the IAEA directly. This body or committee is often referred to as the NEPIO [81]. Thus far, Indonesia has no organization or committee like the NEPIO.

The NEPIO itself can be led by the Prime Minister/Chairman or officials of the Ministry of Energy. In some countries still initiating nuclear programs, the NEPIO is led by the Prime Minister (Bangladesh) or the minister in charge of the energy or electricity sector (Ghana, Sudan, and Uganda) [85–88]. Figure 5 shows the structure of the NEPIO in Bangladesh and Ghana. The NEPIO structure in Bangladesh shows that the Prime Minister is the top leader of this structure, which demonstrates the government's strong commitment to the implementation of the nuclear program. The owner or operator of the nuclear power plant itself is affiliated with the Bangladesh Atomic Energy Commission, an agency established in 1973 that has undergone various types of nuclear energy research and development [89]. Meanwhile, the NEPIO in Ghana is coordinated by the Department of Energy. The GNPPO has members on a high-level advisory board consisting of political representatives and various government agencies, as well as a technical level that forms its core and collaborates with technical organizations or other public and private nuclear technology experts. This technical qualification covers five areas of specialization, namely the Center for Nuclear Program Management, Center for Nuclear Safety Assessment, Center for Positioning and Stakeholder Support, Center for Nuclear Energy Planning, and Center for Public Relations [90].

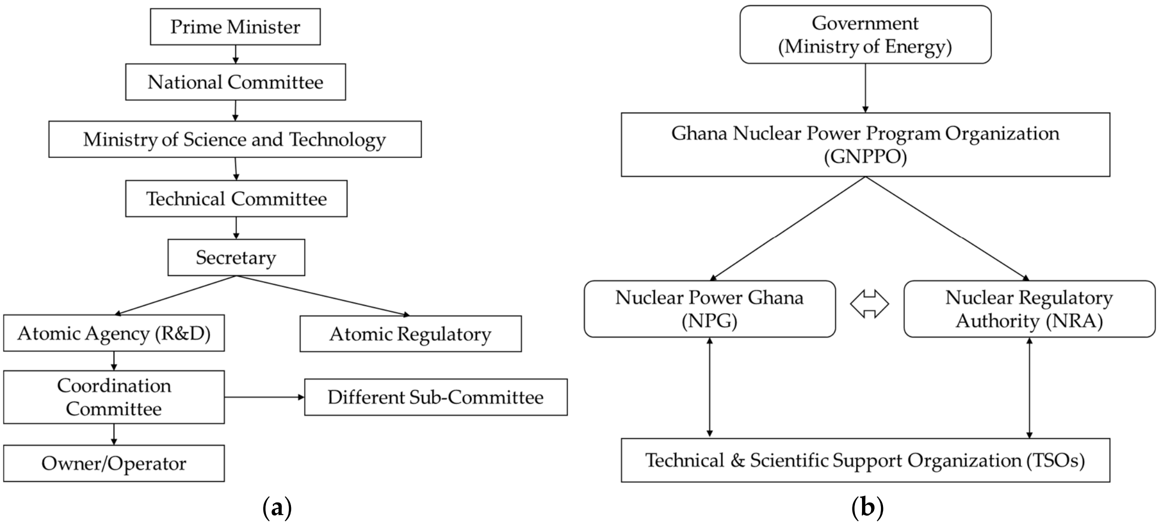

Figure 5. Example of an NEPIO structure: (**a**) Bangladesh; (**b**) Ghana (edited from ref [88–90]).

4.1.3. Prefeasibility Study

Prefeasibility and feasibility studies on NPPs have been carried out in Indonesia, especially by the National Nuclear Energy Agency of Indonesia (Batan, now incorporated in BRIN). These can be seen in Figure 6 and Table 3. A prefeasibility study conducted in Muria, Central Java, in 1996 concluded that NPPs can be feasibly operated in the Java–Bali power system with PWR technology. A study conducted on a site on Bangka Island in 2011 concluded that a nuclear power plant with a capacity of 10 GW could be installed. The NPP locations were divided, one in West Bangka (6 GW) and one in South Bangka (6 GW). This study showed that the LR construction achieves a Levelized Cost of Electricity (LCOE) value of 0.06–0.07 USD/kWh. Meanwhile, a study on the use of SMRs in the West Kalimantan area concluded that SMRs with a capacity of 30 MW could be used in the power system of the region [50,91].

Figure 6. Prefeasibility study locations in Indonesia [92].

Table 3. Summary of previous prefeasibility studies of NPPs [93–95].

No.	Location	Type	Size (MW)	Institution
1	Muria, Central Java	LRs	4 × 1000	Batan (BRIN), IAEA
2	West Bangka, Bangka	LRs	6 × 1000	Batan (BRIN), Bangka Belitung Provincial Government
3	South Bangka, Bangka	LRs	4 × 1000	Batan (BRIN), Bangka Belitung Provincial Government
4	East Kalimantan	LRs	1000	Batan (BRIN), East Kalimantan Provincial Government
5	West Kalimantan	SMRs	30	Batan (BRIN), West Kalimantan Provincial Government
6	Gorontalo	SMRs	90	Batan (BRIN), RAO UES, Rosatom

4.2. Analysis of the Seismic, Tsunamic, and Volcanic Risks

4.2.1. Seismic Investigation

1. Seismic Condition

There are four active fault zones based on their magnitude and slip rate. These zones are as follows: zone 1 has a size greater than 7 Mw with a slip rate of 5 mm/year, zone 2 has a size from 6.5 to 7 Mw with a slip rate of 2–5 mm/year, zone 3 has a size smaller than 6.5 Mw with a slip rate of 2 mm/year, and zone 4 is a potentially active fault. In western Indonesia, there are 43 zone 1 sites spread around the islands of Sumatra and Banten. Meanwhile, in eastern Indonesia, there are 78 zone 1 sites. Zone 2 is found mostly on the islands of Java, Bali, Lombok, Sumbawa, Flores, and Sumba, with a total of 40 locations. The regions of East Kalimantan and South and South East Sulawesi are included in Zone 3, with a total of 19 locations. This can be seen in Figure 7. A fault is the area between two blocks. Faults allow two blocks to move relative to each other. This rapid movement is a tectonic earthquake [96]. Faults in Indonesia result from several tectonic plates, namely the Indo-Australian Plate, the Eurasian Plate, the Philippine Sea Plate, and the Pacific Plate. Slip is a measure of movement between the two blocks.

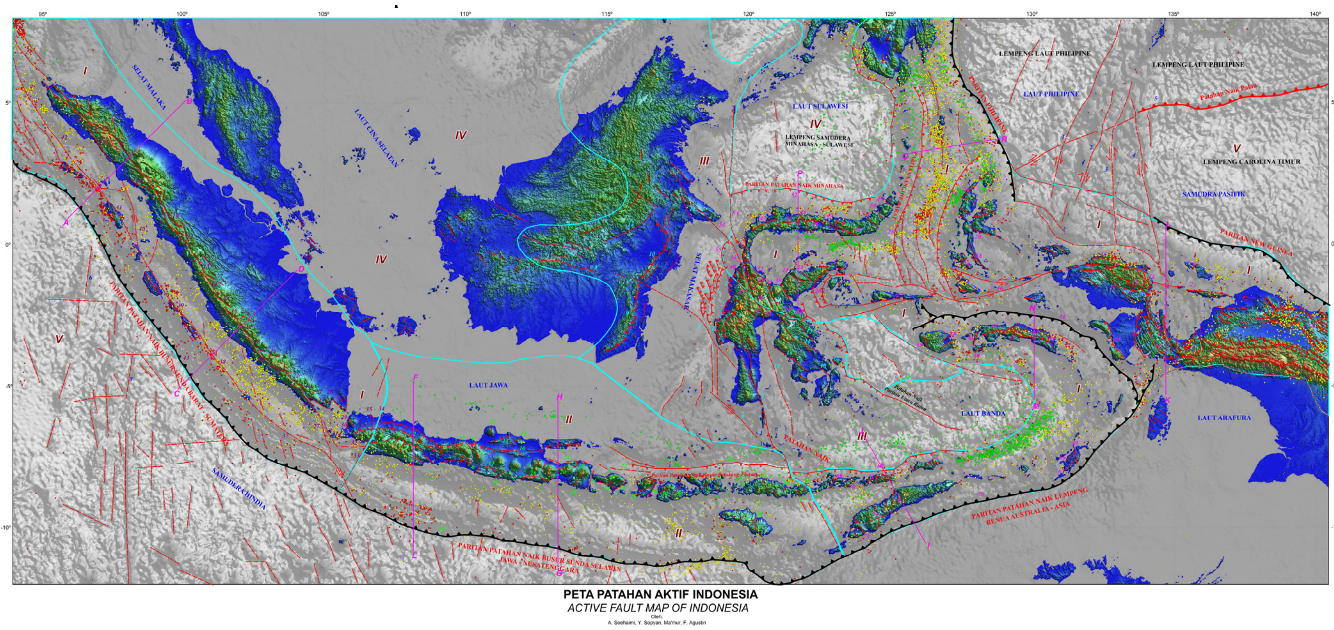

Figure 7. Map of active faults in Indonesia [97].

Figure 8 shows the location of shallow earthquakes during 1922–2022 with a size greater than or equal to 6 M. During this time period, there were more than 1300 earthquake events. In the last 20 years, there have been many earthquakes followed by tsunamis in Indonesia. The earthquakes that caused tsunamis included Aceh (9.2 M) in 2004, Nias (8.6 M) in 2005, Pangandaran (7.6 M) in 2006, and Mentawai (7.7 M) in 2010 [46]. Most of the earthquakes and tsunamis were located in zone 1.

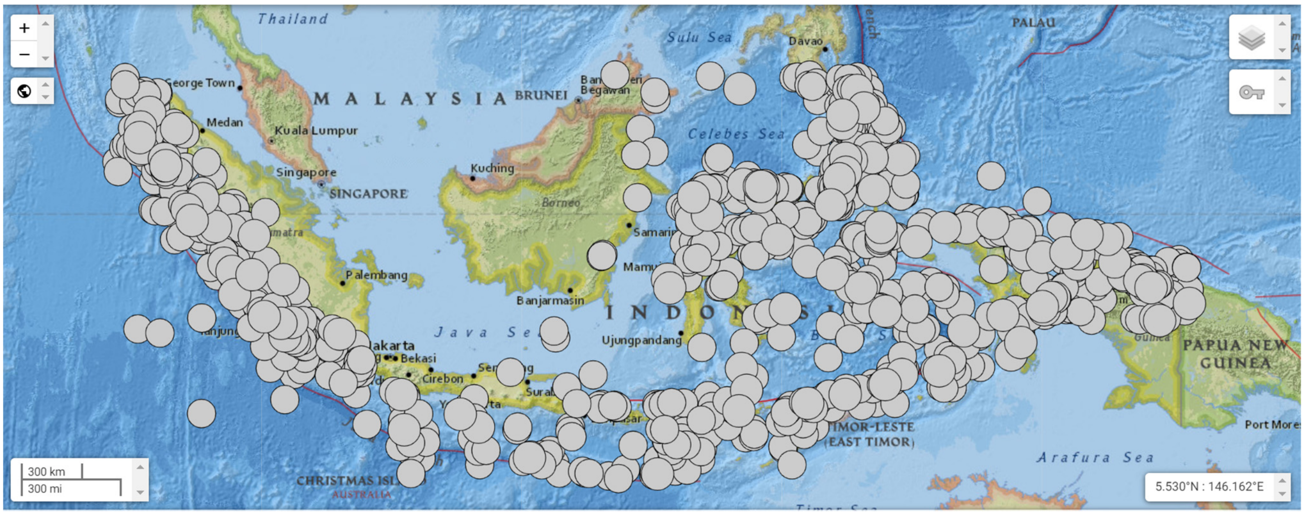

Figure 8. Distribution of earthquakes with a scale >= 6 M with a depth of less than 60 km in 1922–2022 [44].

2. Mitigating Seismic Risks

The Nuclear Energy Supervisory Agency (Bapeten) has issued regulations regarding the evaluation of sites that will be used as locations for NPPs. Those who will build NPPs must create a seismotectonic model to evaluate the danger of ground movement. The evaluation includes determining the attenuation function; deterministic analysis; probabilistic analysis; and an analysis of earthquake wave propagation. This is to ensure that the peak ground acceleration (PGA) at the site with a return period of 10,000 (ten thousand) years does not exceed 0.6 g at the foundation level [98]. Figure 9 is an earthquake hazard map in Indonesia published by the government. The location of NPPs in Korea is located with a maximum PGA value of 0.2 g. NPPs in Belgium are capped at 0.1 g of PGA. The Czech Republic limits the location of NPPs to PGA values below 0.1 g [99]. With a PGA value limit of 0.1 g, several locations have a small seismic risk, namely the east coast of Sumatra, Bangka Belitung, West Kalimantan, Central Kalimantan, South Kalimantan, parts of East Kalimantan, and Merauke Papua.

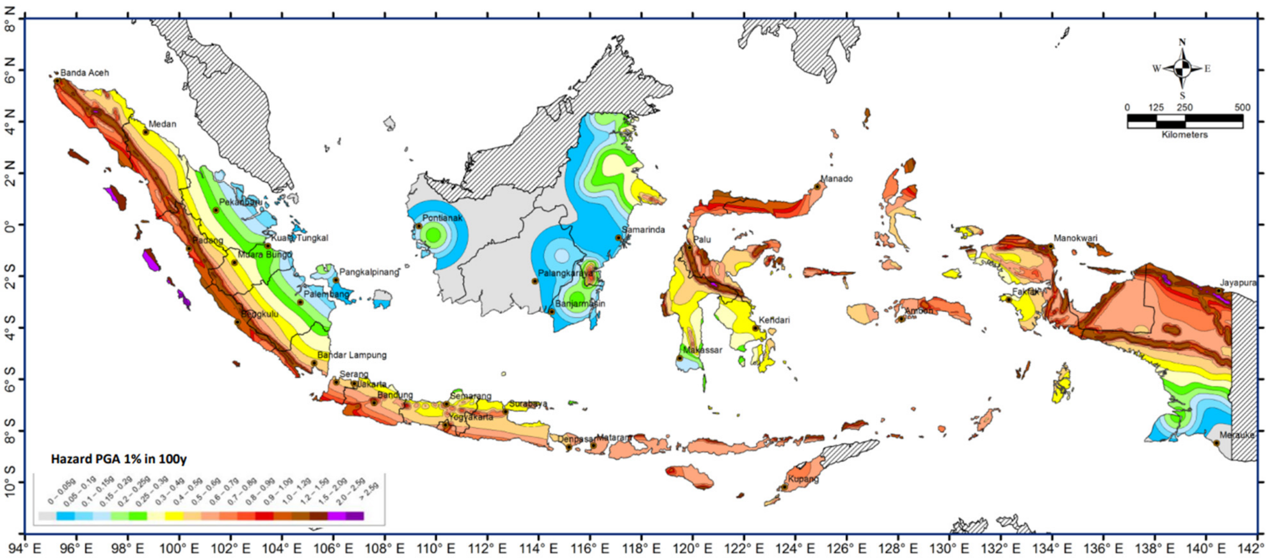

Figure 9. Map of peak acceleration (PGA) in bedrock (S_B) for a 1% exceedance probability in 100 years [100].

4.2.2. Tsunami Investigation and Mitigation

Figure 10 shows locations that have the potential for a tsunami in Indonesia, where the entire west coast of Sumatra and the south coast of Java, which leads to the Indian Ocean, have a high tsunami risk (above 10 m). To reduce the risk of tsunami regarding NPPs, the NPP location is chosen with a maximum tsunami height of 1 m. Areas that have a small risk include the east coast of Sumatra, Bangka Belitung, West Kalimantan, Central Kalimantan, South Kalimantan, northern Java, and South Papua.

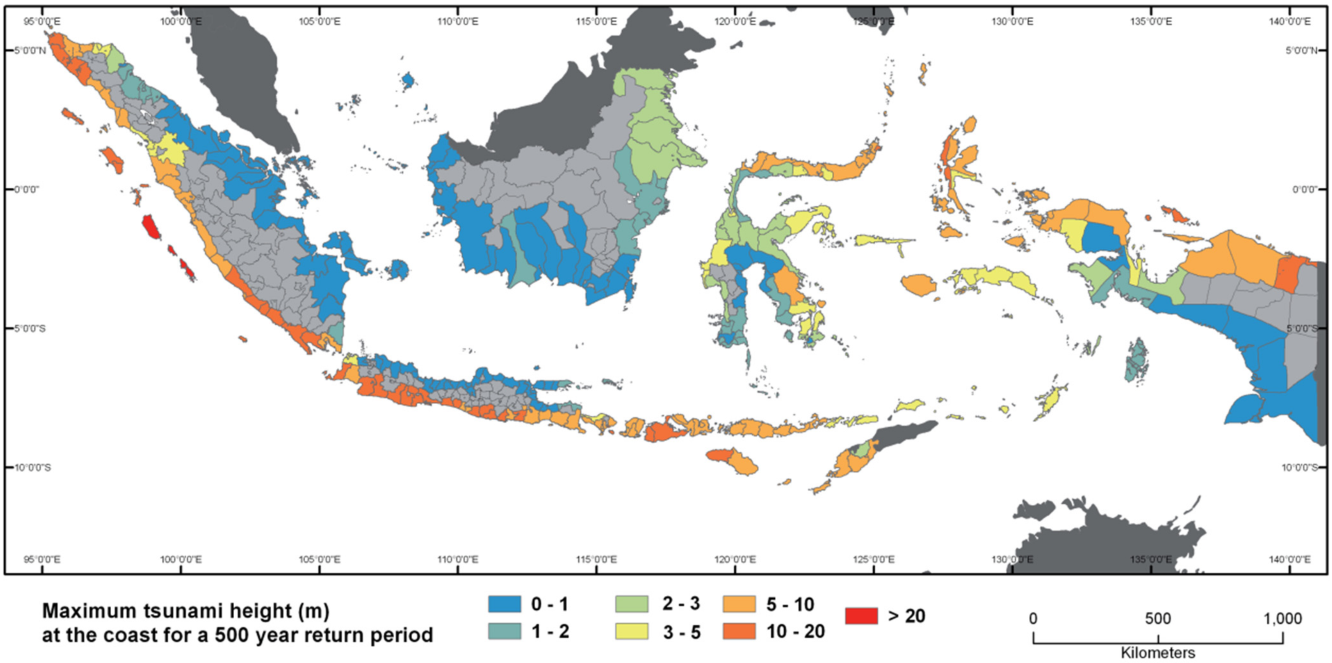

Figure 10. Tsunami potential map in Indonesia [99].

4.2.3. Volcanic Investigation and Mitigation

From Figure 11, it appears that the distribution of volcanoes in Indonesia is concentrated in the Java Trench. These volcanoes are located along the west coast of the island of Sumatra and the south coast of the islands of Java, Bali, and West Nusa Tenggara to the waters of Maluku. Meanwhile, other volcanoes concentrated in the north of the islands of Sulawesi and Halmahera are part of the Philippine Trench. In general, the islands of Kalimantan, Sulawesi (apart from North Sulawesi), northern Java, East Sumatra, East Nusa Tenggara, the Maluku Islands, and Papua have no proximity to volcanoes. These locations have a small risk of volcanic eruptions.

Locations that have a small risk of seismic, tsunamic, and volcanic disasters can be selected as candidate locations for NPPs. Based on a previous risk mitigation analysis, these areas include the east coast of Sumatra, Bangka Belitung, West Kalimantan, Central Kalimantan, South Kalimantan, parts of East Kalimantan, and Merauke Papua.

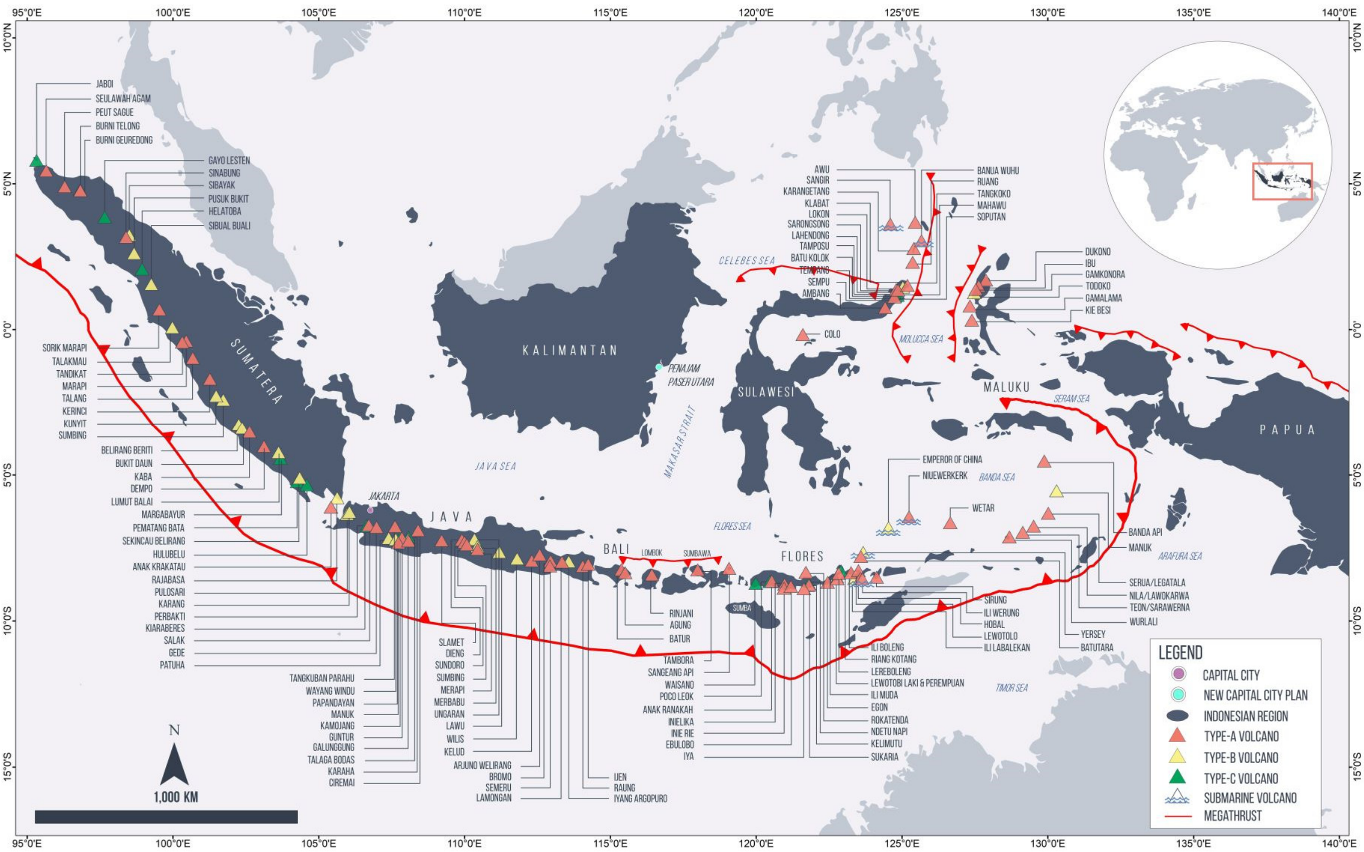

Figure 11. Map of volcanoes in Indonesia [101].

4.3. Analysis of the Use of NPPs in the National Energy Mix

4.3.1. Potential Energy Resources

In 2022, the proven coal reserves were 34.7 billion tons and the actual coal production was 687.40 million tons; with this production, coal reserves will be finished in about 50 years [24]. Indonesia is a net oil importer, where oil consumption exceeds domestic production. In 2022, Indonesia's total oil reserves were 2272 MMSTB, with an output of 612 million barrels per day. Thus, if no new reserves are found, with the same amount of production, Indonesia's oil reserves will last about 6 years. Meanwhile, Indonesia has total natural gas reserves of 36.34 TCF, and production is 6490 MMSCFD. Hence, natural gas reserves will last about 15 years [102].

Hydropower potential in Indonesia is 75 GW, where there are many locations outside Java Island which have high demand for electrical energy, namely Papua with 22.3 GW, Kalimantan with 16.8 GW, and Sulawesi with 19.2 GW. The installed capacity of hydropower was only 5.5 GW in 2022, so the utilization is still around 7.3% [26,60,103]. Some of the obstacles that affect the low utilization of hydropower include geographical factors, locations that are far from the demand for electrical energy loads, and ecological problems [104]. With the project's economic approach and for it to not conflict with the location of protected areas, tourism zones, and residential areas, it is estimated that only around 26.3 GW of hydropower can be developed [105,106]. Indonesia has a total geothermal energy potential of 23.96 GW, consisting of 9.34 GW of resources and 14.63 GW of reserves. The installed capacity of geothermal power plants in Indonesia is 2.1 GW, the second largest in the world in 2022. The geothermal energy utilization is still 8.76% [26,60,107]. Obstacles that occur in the geothermal sector during the upstream phase include the risks of the exploration phase, including low heat sources found (uneconomical), uneconomical capacity of wells, and operational constraints such as scaling and corrosion, and high capital costs. The obstacles in the downstream phase are low tariffs and the location of the demand for electrical energy, which is far from geothermal sources [35]. The potential for solar energy in Indonesia is 208 GW and wind is 61 GW, while the utilization of these energy types is still very low, where the existing capacity of solar PVs is 83 MW and wind is 130 MW [26,103]. Solar PVs and wind have intermittent characteristics, where the production of electric power fluctuates depending on environmental conditions. Intermittent renewable energy has poor inertia but requires a low marginal cost. This intermittency increases the variance in the energy supply in the electricity system. To address this, a hybrid system can be used to overcome fluctuations in the production of electrical energy, for example, a thermal generator such as a gas engine or gas turbine and one battery [108–110]. Biomass potential in Indonesia is around 32.7 GW, of which the largest is in Sumatra at 15.6 GW and Java at 9.2 GW [103].

4.3.2. Electricity Condition

In 2022, sales of electrical energy in Indonesia amounted to 273.36 TWh, originating from the household segment with 116.10 TWh (42.41%), business with 50.53 TWh (18.46%), public with 18.65 TWh (6.81%), and industry with 88.50 TWh (32.32%). The production of electrical energy in 2022 was 308 TWh, which came from various power plants, as shown in Figure 12. The electricity production is supplied by a coal-fired power plants (66%), natural gas (16.70%), hydropower (7.26%), and geothermal power (5.41%), and the rest comes from diesel and some renewable energy. The total capable capacity of PT. PLN (Persero), Independent Power Producer (IPP), and rent is 61.73 GW. Indonesian power generations are dominated by a coal-fired power plants, contributing 34 GW (55%) [26].

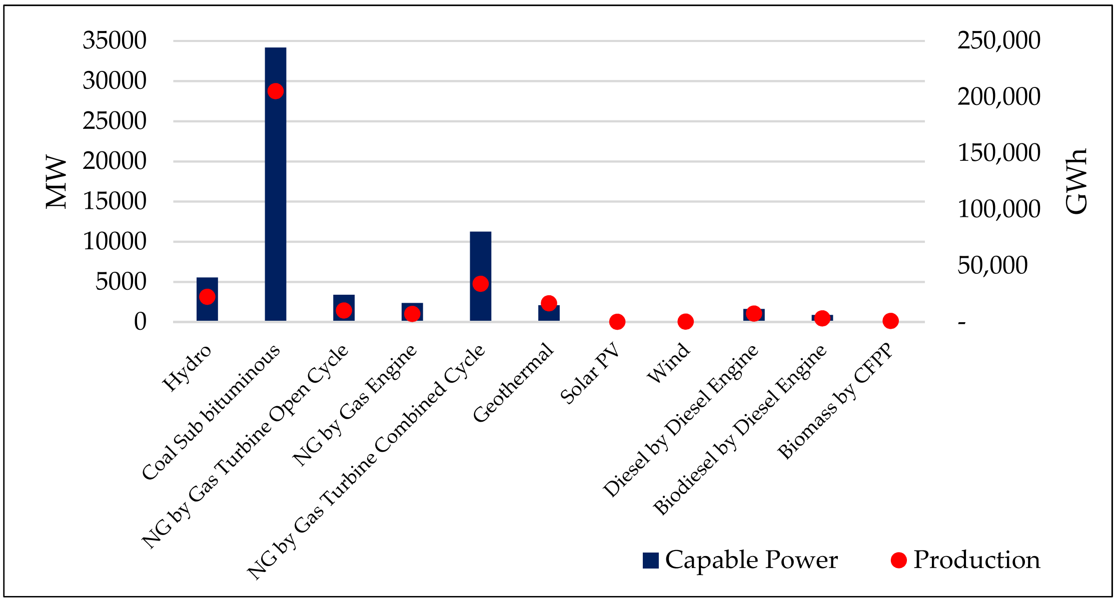

Figure 12. The condition of Indonesia's electricity in 2022 [26].

Indonesia and China have similarities regarding the large contribution of coal in the electricity production. Coal has a contribution of 66% to electric energy production in Indonesia, while in China it was 61% in 2022. Indonesia is still experiencing an increasing trend in coal's contribution to its electric energy production, while China has experienced a decline. The contribution of coal in Indonesia rose from 39% in 2010 to 66% in 2022. The contribution of coal in China fell from 77% in 2010 to 61% in 2022 [111,112]. In reducing GHG emissions, China has implemented a policy of utilizing NPPs and renewable energy and reducing the contribution of coal. The contribution of NPPs in China increased from 1% in 1995 to 5% in 2022. Fossil fuels and NPPs are used for energy security in China's energy policy [113].

4.3.3. Assumptions and Simulations

1. Economics of NPPsLarge Reactors (LRs)

- Large Reactors (LRs)

The cost of NPPs is characterized by relatively large capital costs compared to other base-load power plants. Capital costs consist of overnight, construction, and financing costs [114,115]. Figure 13 shows the capital cost trend with various discount rates. Even though they are members of the Organization for Economic Co-operation and Development (OECD), there are significant cost differences between France, the USA, Japan, Russia, and Korea. The capital cost value of Korea is lower than the USA and France, as they are pioneers and the largest users of NPPs in the world [77]. Several factors that drive the relatively low capital costs in Korea are design standardization, stable regulatory regimes, and the building of many identical and large-capacity reactors on the same site [116–118]. In this simulation, optimistic (typical Korean LRs) and conservative (typical French LRs) scenarios are used.

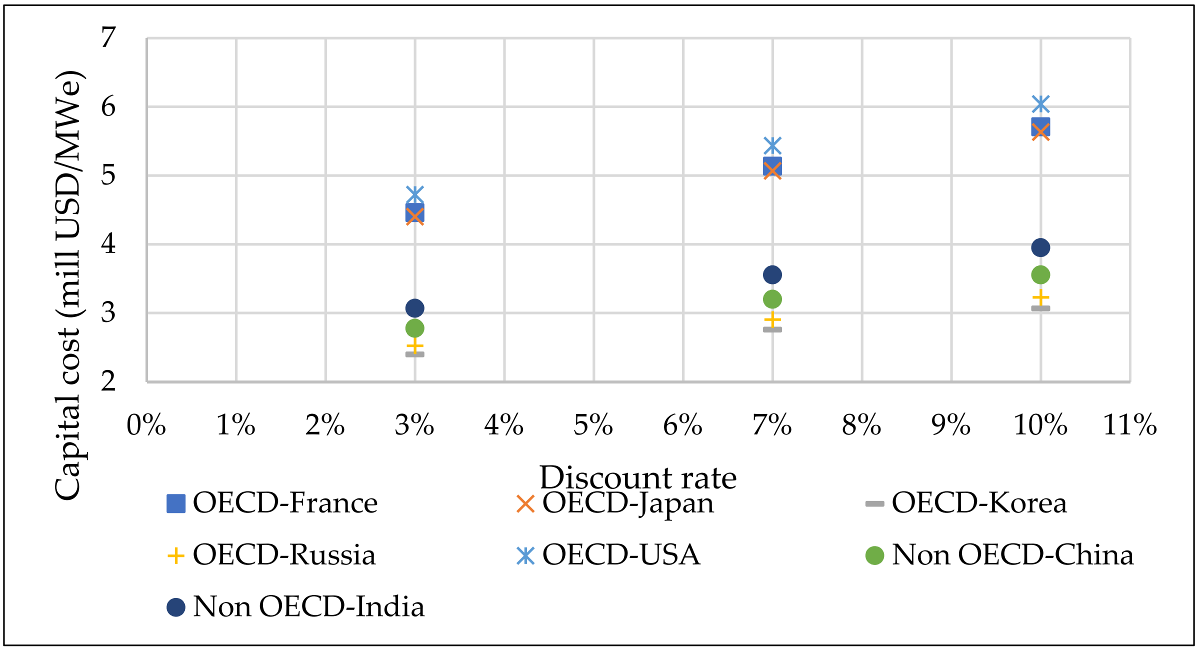

Figure 13. Comparison of capital cost LRs of various countries [119].

- Small Modular Reactors (SMRs)

A study discussing the economics of SMRs compared to the CFPP and natural gas combined cycle found that SMRs were economically competitive in remote areas or small electrical grids. When the coal price is in the range of 80-120 USD/mt and the carbon tax is 30 USD/mt CO_2, SMRs can compete economically with a maximum discount rate of 10%. Meanwhile, if the natural gas price is above 10 USD/MMBtu and the carbon tax is 30 USD/mt CO_2, SMRs will also be suitable for use with a maximum discount rate of 10%. This study concludes that the economics of SMRs are greatly influenced by electricity prices related to the guarantee of purchasing electrical energy in the feasibility study. The greater the value of the discount rate and overnight costs, the higher the electricity price; thus, the economics of SMRs can be achieved [120]. In this simulation, the typical SMRs used for the simulation are HTR-PM and VBER 300 Mwe because they are related to the Technology Readiness Level (TRL) value, which exceeds the requirements of the Indonesian government. In addition, the HTR-PM developed by China has also been applied commercially, and the capital cost is relatively low [121–123]. The HTR-PM uses a High-Temperature Gas-Cooled Reactor with a nominal capacity of 210 Mwe. The VBER 300 MWe is a commercial scale of KLT-40 S, which has 300 Mwe capacity, as shown in

Figure 14. In this simulation, optimistic (HTR-PM) and conservative (VBER 300 Mwe) scenarios are used.

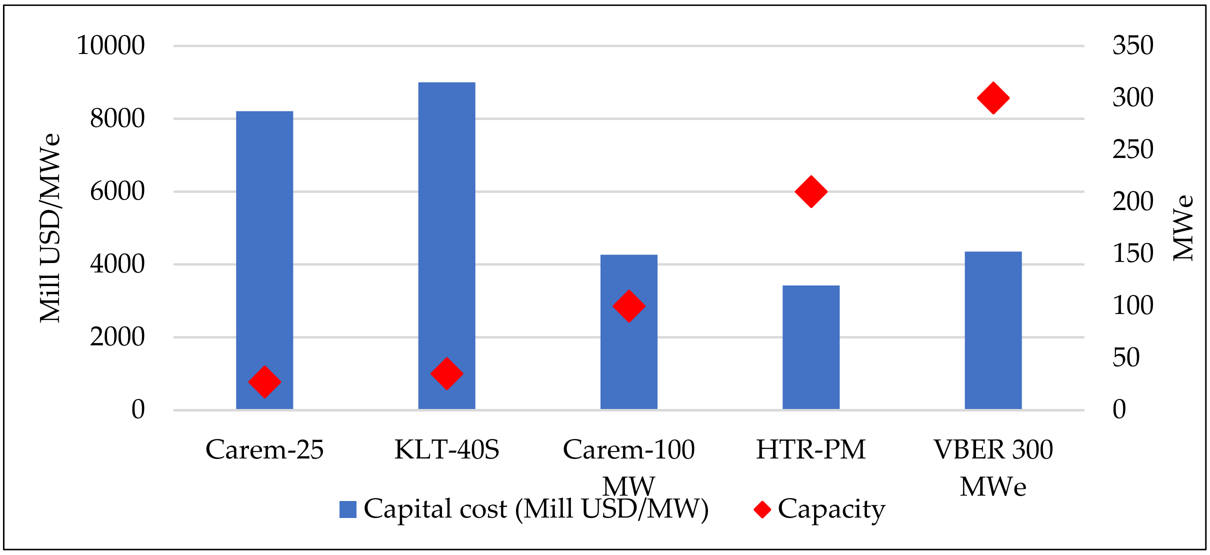

Figure 14. Comparison of capital costs of SMRs of various types [122].

2. Scenario assumptions

Table 4 shows the assumptions used as the basis for scenarios in the energy mix simulation up to the year 2060. The BaU scenario allows CFPPs to continue to dominate the energy mix in the future due to the abundance of coal resources in Indonesia, relatively low capital costs, and relatively inexpensive LCOE. Meanwhile, scenarios (a), (b), (c), (d), (e), (f), and (g) are based on efforts to reduce CO_2 emissions. In these scenarios, CFPPs, as the largest CO_2 contributors, are expected to have a 0% contribution in 2060. In these various scenarios, the use of renewable energy is fully optimized, assuming a utilization of 75% of the existing potential. Energy deficiencies will be met by natural gas and NPPs. The optimistic and conservative scenarios are based on the costs of each NPP. The optimistic scenario uses typical Korean LRs and the SMR HTR-PM. Meanwhile, the conservative scenario uses typical France LRs and VBER-300 MWe.

Table 4. Summary of scenarios applied.

Scenario	Simulation Years					Ref.
	2030	2038	2050	2060		
BaU	- CFPPs 64% - RE 22% - NG 12%	- Dominated by CFPPs - RE 28%	- Dominated by CFPPs - RE 31%		Dominated CFPPs	[60,84,103]
CFPPs retired [1,2]	- CFPPs 64% - RE 22% - NG 12%	-Stop building CFPPs		- Max. cap. geothermal 14.4 GW (75% utilization of potential) - Max. cap. hydro 37.5 GW (75% utilization of potential) - Max. cap. biomass 24.5 GW (75% utilization of potential) - Max. cap. solar PVs 155 GW (75% utilization of potential) - Max. cap. wind 45.5 GW (75% utilization of potential) - Min. RE 35% of energy mix (assumption)	CFPPs 0%	
(a) 0% NPPs					NPPs 0%	[40,60,124]
(b) 5% NPPs					NPPs 5% (optimistic)	[40,60,124]
(c) 10% NPPs					NPPs 10% (optimistic)	[40,60,124]
(d) 15% NPPs					NPPs 15% (optimistic)	[40,60,124]
(e) 5% NPPs					NPPs 5% (conservative)	[40,60,124]
(f) 10% NPPs					NPPs 10% (conservative)	[40,60,124]
(g) 15% NPPs					NPPs 15% (conservative)	[40,60,124]

[1] Operation of NPPs for the first time is assumed in 2035; [2] NPPs consist of 75% LRs and 25% SMRs.

Power systems are designed to respond to fluctuations in supply and demand. Power systems contain several types of power plants in order to maintain quality, reliability, security, and economic aspects. In term of flexibility, power plants are divided into three categories: base-load, peaking, and load-following power plants. Power generation that has a large scale and is economical can function as a base load, for example, steam power plants. Steam power generation that comes from burning coal or nuclear reactors has a very low ramping rate, so it is usually used as a base load. This type of generator cannot be used to respond to power demand fluctuations [125]. Peaking power plants only operate at peak load for a short duration. Meanwhile, load-following power plants function to balance the demand–supply of the electricity system at any time, for example, hydropower and gas turbine power generation [126]. This type of generator has a high ramping rate (>5%/min) to overcome fluctuating supply and demand [127].

Variable renewable energy (VRE) such as solar PVs and wind have intermittency properties (electrical energy production depending on the weather), which can affect the quality and reliability of the electric power system. This variability is a challenge from both technical and economic aspects [128,129]. Some ways to eliminate this variability include expanding and strengthening the electric power system, early estimates of VRE, demand response, flexible use of power plants, and energy storage. High capital investment cost is required in solutions for the expansion and strengthening of the electric power system as well as the use of flexible power plants [129]. Energy storage is widely recognized as a solution to this variability. The types of energy storage used include pumped hydro storage, batteries, and compressed air energy storage [130]. The use of energy storage in power systems that utilize VRE will reduce power fluctuations, increase power system flexibility, and enable the delivery of energy produced by VRE [131,132].

With the increasing use of VRE, energy storage capacity has also experienced a high increase. Pumped hydro storage is the most widely used type of storage. In 2020, pumped hydro storage capacity was 160 GW. Meanwhile, battery capacity in 2020 was 9.2 GW [133]. There are various types of battery energy storage, including Lead Acid, Lithium-Ion (Li-Ion), Sodium Sulfur (Na S), Sodium Chloride, and Nickel Cadmium. Li-Ion batteries are the most widely used type because the technology is mature. The use of battery energy storage in the power system is able to accommodate VRE penetration of around 30–50%, reducing expansion costs and reducing power loss [129]. Installing energy storage of 0.04–0.05% of the total electrical energy production will enable VRE penetration of up to 30% while maintaining the flexibility and quality of the power system [134,135]. In this research, the type of energy storage battery used is Li-Ion. The amount of Li-Ion energy storage capacity is assumed to be 0.05% of the total electrical energy production. Hence, the technical and economic variables in this simulation are VRE technology with Li-Ion batteries.

Tables 5–7 show the data related to modeling assumptions such as load growth, transmission and distribution losses, load curve, technical and economic characteristics of power generations, etc. The CO_2 emission parameters produced by each power generation type during the production of electrical energy refer to the Intergovernmental Panel on Climate Change (IPCC) embedded in the LEAP software [9,136,137].

Table 5. Summary of input parameters.

Input Parameters	Metric	Data	Ref.
Discount rate [a]	%	10%	[138,139]
Inflation rate [b]	%	5%	[140–142]
Population	Mill. persons	275.77 (2022)	[143]
Population	Mill. persons	334.59 (2060)	[144]
Population growth	% p.a.	0.51%	[144]
Electricity demand history		Table A1	[26,145–148]
Demand growth	%	4.28%	[60,149]
Household	%	2.35%	[60,149]
Business	%	4.16%	[60,149]
Public	%	4.14%	[60,149]
Industry	%	5.60%	[60,149]

Table 5. *Cont.*

Input Parameters	Metric	Data	Ref.
Transportation	TWh	0 (2030); 39 (2060)	[60,149]
T n D losses	%	8.75% (2022)–7% (2060)	[26,145–148]
Load shape		Figure A1	[150]
Fuel cost		Table A3	[26,82,140,146–148,151–154]
Lifetime	Years	Table 5	[52,54,82,119]
Efficiency	%	Table 5	[52,54,82,119]
Maximum availability	%	Table 5	[52,54,77,82,119]
Solar PV availability	%	Figure A2	[155]
Wind availability	%	Figure A3	[156]
Capital cost	USD/MW	Table 5	[82,119,122,157,158]
Capacity credit	%	Table 5	[82,119,122,157]
Fixed O/M Cost	USD/MW	Table 6	[57,82,119,122,154,157]
Variable O/M Cost	USD/MWh	Table 6	[82,119,122,157,159]
Liability cost (NPPs) [c]	USD/MW	66,667	[158]
Liability cost (SMRs) [d]	USD/MW	66,667	[158]
Decommissioning [d]		0.01 USD/kWh	[160]
Reserve margin	%	39%	[60,82]

[a,b] Assumed to be greater than the average of 30 years of data; [c] calculated with the assumption of a liability of 1 T IDR and LR capacity of 1000 MW at an exchange rate of 1 USD of 15,000 IDR; [d] calculated with the assumption of a liability of 250 billion IDR and SMR capacity of 250 MW at an exchange rate of 1 USD of 15,000.00 IDR.

Table 6. Data of input parameters (technical and capital cost).

Power Generation Technology	Lifetime	Efficiency	Maximum Availability	Capacity Credit	Capital Cost (Thousand USD/MW)				
	(years)	(%)	(%)	(%)	2020	2030	2040	2050	2060
Hydro	80	100	41	51	2203	2203	2203	2203	2203
Sub-bituminous CFPP (USC)	40	35	90	100	1469	1469	1469	1469	1469
Gas turbine open cycle (NG)	30	33	97	100	770	730		680	
Gas engine (NG)	30	45	97	100	800	800		780	
Gas turbine combined cycle (NG)	30	56	95	100	944	944	944	944	944
Geothermal [a]	30	100	90	80	3724	3567	3462	3360	3360
Solar PV	25	100	Figure A2	22	1.154	896	786	689	604
Wind	25	100	Figure A3	35	1252	1217	1154	1094	1038
Li-Ion 6 hours (moderate)	15	85	25	25	2466	1210	1059	908	
Diesel engine (diesel fuel)	30	45	97	100	800	800		780	
Diesel engine (biodiesel)	30	45	97	100	800	800		780	
CFPP (biomass)	40	35	90	100	1469	1469	1469	1469	1469
Typical Korea LRs [b]	60	36	83	100	3133	3133	3133	3133	3133
Typical France LRs [b]	60	33	83	100	5772	5772	5772	5772	5772
SMR HTR-PM [b]	60	42	83	100	3485	3485	3485	3485	3485
SMR VBER 300 Mwe [b]	60	24	83	100	4415	4415	4415	4415	4415

[a] Includes exploration and confirmation costs; [b] capital cost includes capital cost of typical technology plus liability (insurance in Indonesian regulations).

Table 7. Data of input parameters (fixed and variable costs).

Power Generation Technology	Fixed O&M Cost USD/MW/Year			Variable Cost (USD/MWh)		
	2020	2030	2050	2020	2030	2050
Hydro	37,700	36,200	33,600	0.65	0.62	0.58
Sub-bituminous CFPP (USC)	56,600	54,900	53,200	4.70	4.70	4.70
Gas turbine open cycle (NG)	23,200	22,500	21,800	3.90	3.90	3.90
Gas engine (NG)	8000	8000	7760	6.40	6.00	5.80
Gas turbine combined cycle (NG)	23,500	22,800	22,100	2.30	2.23	2.16
Geothermal	50,000	43,000	35,500	0.25	0.22	0.18
Solar PV	14,400	10,000	8000	-	-	-

Table 7. *Cont.*

Power Generation Technology	Fixed O&M Cost USD/MW/Year			Variable Cost (USD/MWh)		
	2020	2030	2050	2020	2030	2050
Wind	60,000	51,000	43,200	-	-	-
Li-Ion 6 hours (moderate)	62,000	30,000	23,000			
Diesel engine (diesel fuel)	8000	8000	7760	6.40	6.00	5.80
Diesel engine (biodiesel)	8000	8000	7760	6.40	6.00	5.80
CFPP (biomass)	56,600	54,900	53,200	4.70	4.70	4.70
Typical Korea LRs	138,000	138,000	138,000	4.30	4.30	4.30
Typical France LRs	138,000	138,000	138,000	4.30	4.30	4.30
SMR HTR-PM	114,000	114,000	114,000	4.30	4.30	4.30
SMR VBER-300 MWe	114,000	114,000	114,000	4.30	4.30	4.30

3. Annualized production and investment cost and GHG emission calculation

The calculation of power plant production costs in LEAP is based on the capital costs for building new processes, the salvage values for decommissioning processes, the fixed and variable operating and maintenance costs, the fuel costs, and the environmental externality values (i.e., pollution damage or abatement costs). These cost components are added up annually in annualized costs. The total cost of production is calculated from the sum of all discounted costs [114,161]. This is shown in Formula (1). In this simulation, externality costs are not taken into account. Meanwhile, the investment cost is calculated from the addition of power generation capacity.

$$\begin{aligned} &\mathit{Total\ production\ cost} \\ &= \left\{\sum_y \left[\frac{1}{(1+d)^{y-y_b}} \sum_{pgt} \left(\mathit{annualized\ capital\ cost} + \mathit{fixed\ costs} * \mathit{capacity}_{PGT,y} + \mathit{operational\ cost} * \sum_t \mathit{generation}_{PGT,y,t} \right)\right]\right\} \end{aligned} \quad (1)$$

where the components are as follows:

Y : year;
Yb : base year;
PGT : power generation technology;
t : time step;
d : discount rate (%).

GHG emissions produced by power generation include nitrous oxide, carbon dioxide, and methane, which are calculated according to the IPCC Tier-1 emission factors embedded in LEAP [54,114].

$$CE = \sum_p \sum_f EF_{f,p} x \frac{1}{E_p} x P_p \quad (2)$$

where the components are as follows:

CE : GHG emissions;
$EF_{f,p}$: GHG emission factor from one unit of primary fuel type f consumed for producing electricity through technology p;
E_p : the efficiency of technology p;
P_p : the output power from technology p.

Each scenario simulated in LEAP has been assumed and regulated in relation to the type of technology used, the target ratio of renewable energy use in the energy mix, and so on, as in Table 4 in the previous section. Then, LEAP works according to these assumptions with a mathematical model to calculate the amount of production and investment costs in each scenario, as in Equation (1). The amount of GHG emissions produced by power plants is calculated using Equation (2). Least cost optimization is used to obtain the lowest cost using the next energy modeling system for optimization (NEMO) solver. NEMO type CBC is a free and open-source mixed-integer linear programming solver [114]. The simulation results in various scenarios are discussed in the next section.

4.3.4. Simulation Result

Indonesia's population in 2022 was 275.77 million and is estimated to increase to 334.60 million by 2060 assuming an average growth of 0.51% per year (moderate scenario) [143]. Electric energy consumption per capita was 1173 kWh in 2022 and will increase to 4023 kWh per capita in 2060; this assumption is slightly below the report issued by the International Energy Agency (IEA) [149,162,163]. The projection of electrical energy demand until 2060 is shown in Figure 15, where the industrial sector dominates future electrical energy demand. This demand projection towards 2060 is used by all energy mix scenarios whether using CFPPs or not.

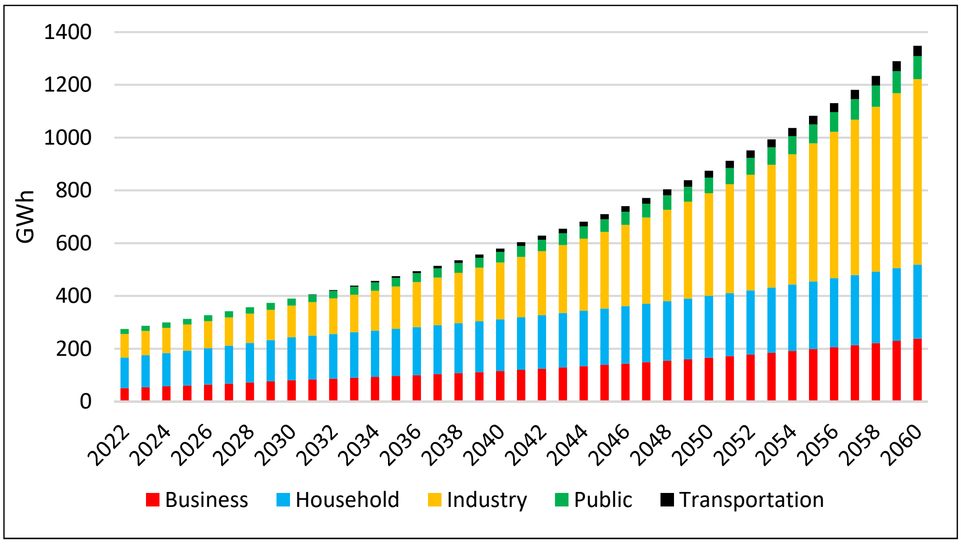

Figure 15. Projection of Indonesia's electricity demand until 2060.

1. BaU Scenario

In the BaU scenario shown in Figure 16, CFPPs are still dominant in 2060, and the use of renewable energy is assumed to be above 35% of the total electrical energy produced. In 2060, electrical energy production will be 1449 TWh, coming from hydropower with 134.7 TWh (9.3%), coal with 755.1 TWh (52.1%), natural gas with 169.5 TWh (11.7%), geothermal power with 113.5 TWh (7.8%), solar PVs with 146 TWh (10.2%), wind with 31.5 TWh (2.2%), diesel fuel with 3.3 TWh (0.2%), biodiesel with 2.2 TWh (0.15%), and biomass with 93.4 TWh (6.4%). The total electricity generation capacity in 2060 will be 397.5 GW, as shown in Figure 17. This generation comes from hydropower with 37.5 GW (9.4%), CFPPs with 122.3 GW (30.77%), natural gas with 25.8 GW (6.5%), geothermal power with 14.4 (3.6%), solar PVs with 95 GW (24%), wind with 26.4 GW (6.6%), diesel fuel with 0.5 GW (0.1%), biodiesel with 0.5 GW (0.1%), biomass with 15.4 GW (3.8%), and Li-Ion batteries with 120 GW (15%).

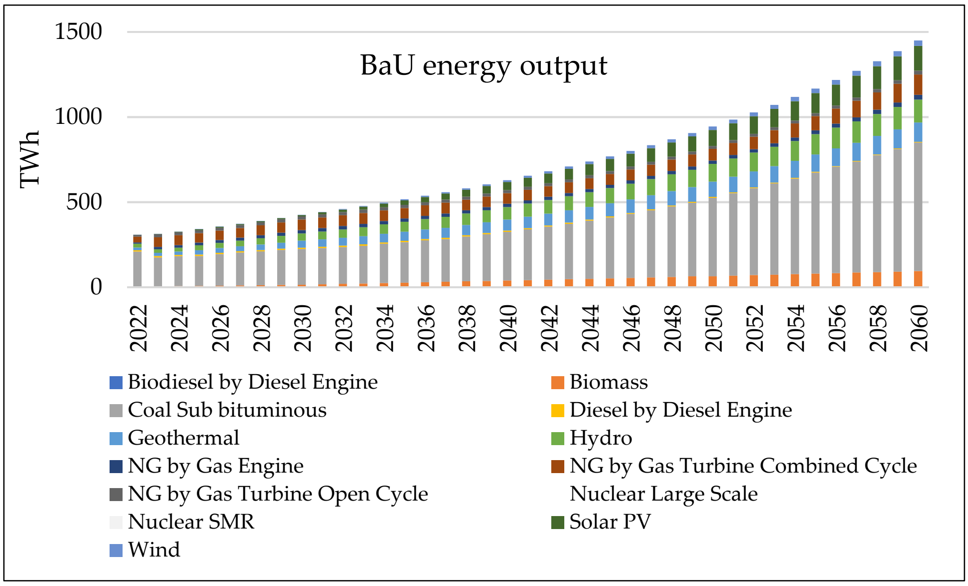

Figure 16. BaU scenario of Indonesia's electricity energy production until 2060.

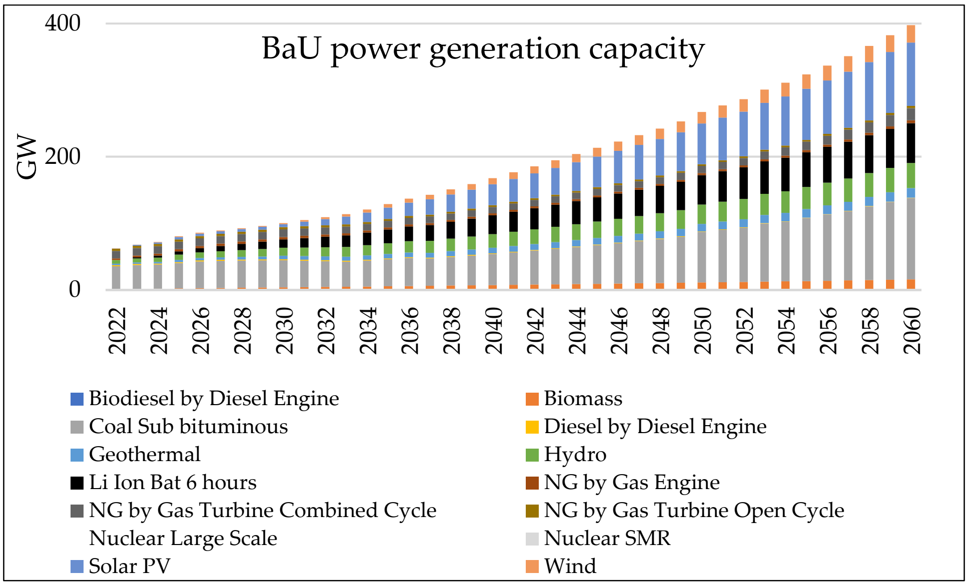

Figure 17. BaU scenario of Indonesia's power generation capacity until 2060.

2. Scenario A

This scenario is based on the retirement of CFPPs in 2060 and the use of NPPs still being 0% in 2060. In this scenario, shown in Figure 18, the total electrical energy produced in 2060 is 1450 TWh, of which 134.7 TWh comes from hydropower (9.3%), coal is 0 TWh (0%), natural gas is 789.1 TWh (54.4%), geothermal power is 113.5 TWh (7.8%), solar PVs is 238.2 TWh (16.4%), wind is 54.4 TWh (3.8%), diesel fuel is 0 TWh (0%), biodiesel is 0 TWh (0%), and biomass is 120.2 TWh (8.3%). The total electricity generation capacity in 2060 will be 501 GW, as shown in Figure 19. The power generation comes from hydropower with 37.5 GW (7.5%), CFPPs with 0 GW (0%), natural gas (gas engine, gas turbine open cycle, and gas turbine combined cycle) with 103.1 GW (20.6%), geothermal power with 14.4 (2.9%), solar PVs with 155 GW (30.9%), wind with 45.5 GW (9.1%), diesel fuel with 0.5 GW (0.1%), biodiesel with 0.5 GW (0.1%), biomass with 24.5 GW (4.9%), and Li-Ion batteries with 120 GW (24%). In this scenario, more than half of the electrical energy produced comes from natural gas.

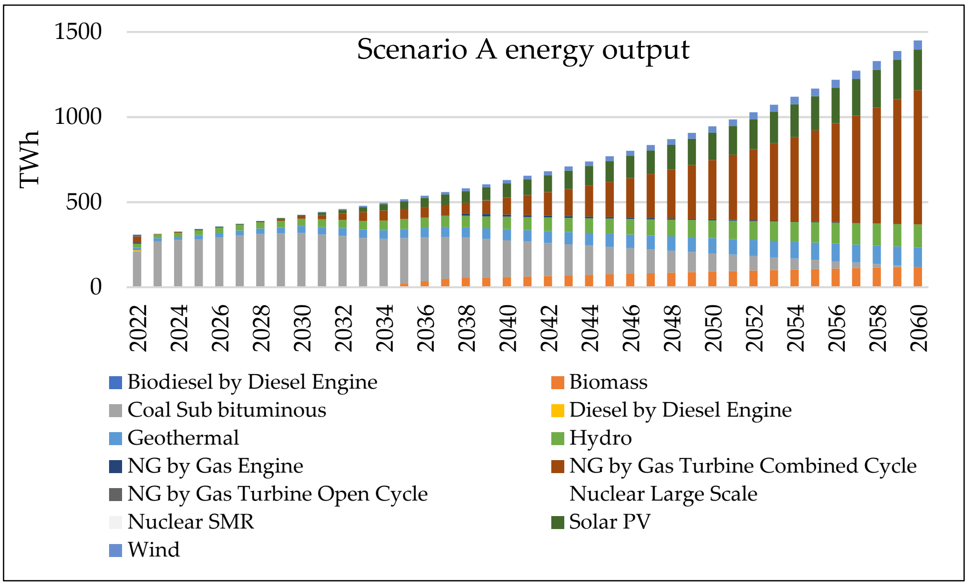

Figure 18. Scenario A of Indonesia's electricity energy production until 2060.

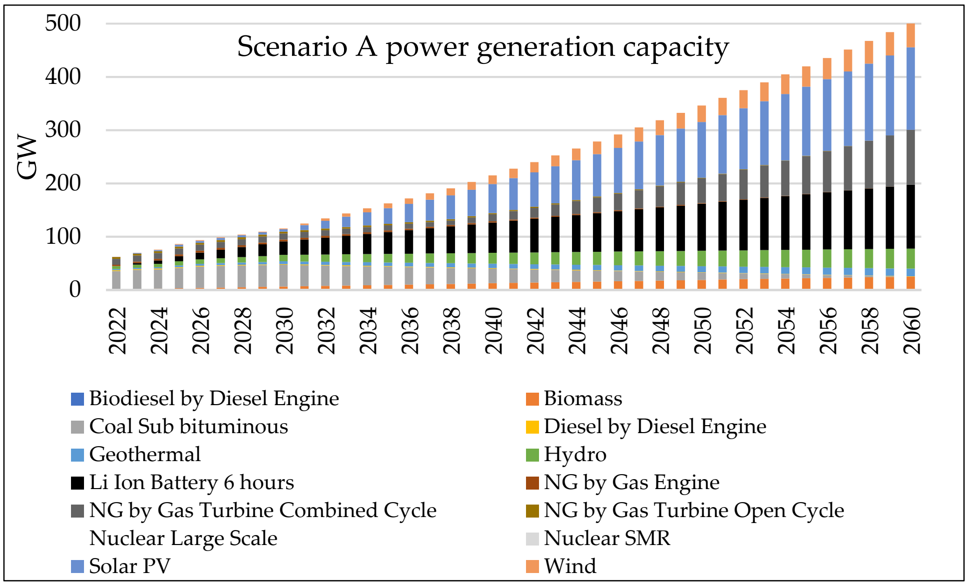

Figure 19. Scenario A of Indonesia's power generation capacity until 2060.

3. Scenario B and E

Scenarios B and E are basically the same, only with differences in NPP technology. These scenarios are based on the retirement of CFPPs in 2060, and the use of NPPs is 5% in 2060. In this scenario, shown in Figure 20, the total electrical energy produced in 2060 is 1450 TWh, of which 134.7 TWh comes from hydropower (9.3%), coal is 0 TWh (0%), natural gas is 729.4 TWh (50.3%), geothermal power is 113.5 TWh (7.8%), solar PVs is 238.2 TWh (16.4%), wind is 54.4 TWh (3.8%), diesel fuel is 0 TWh (0%), biodiesel is 0 TWh (0%), biomass is 108.2 TWh (7.5%), NPP LRs is 53.8 TWh (3.7%), and NPP SMRs is 17.4 TWh (1.2%). The total electricity generation capacity in 2060 will be 504.3 GW, as shown in Figure 21. The power generation comes from hydropower with 37.5 GW (7.4%), CFPP with 0 GW (0%), natural gas (gas engine, gas turbine open cycle, and gas turbine combined cycle) with 96.6 GW (19.2%), geothermal power with 14.4 (2.9%), solar PVs with 155 GW (30.7%), wind with 45.5 GW (9%), diesel fuel with 0.5 GW (0.1%), biodiesel with 0.5 GW

(0.1%), biomass with 24.5 GW (4.9%), NPP LRs with 7.4 GW (1.5%), NPP SMRs with 2.4 GW (0.5%), and Li-Ion batteries with 120 GW (23.8%).

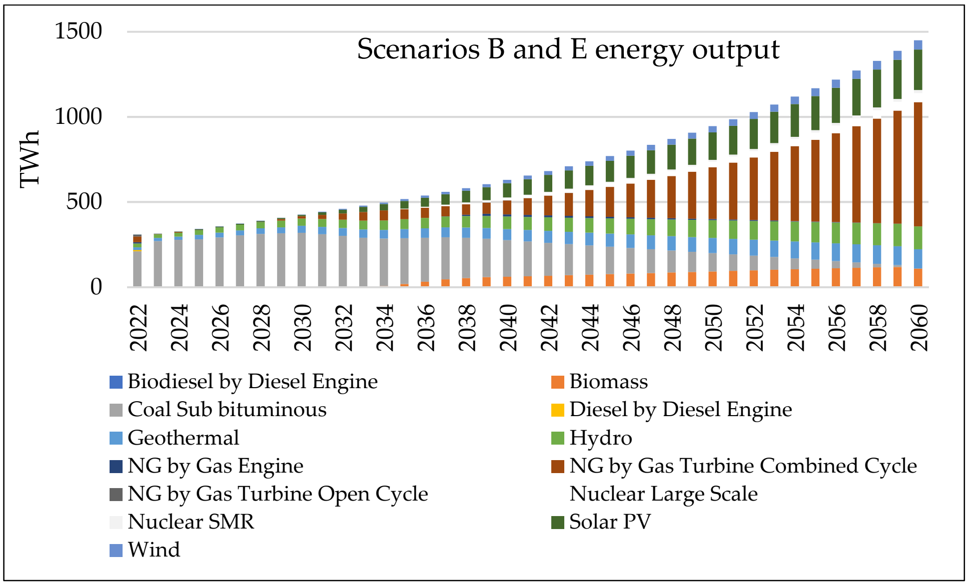

Figure 20. Scenarios B and E of Indonesia's electricity energy production until 2060.

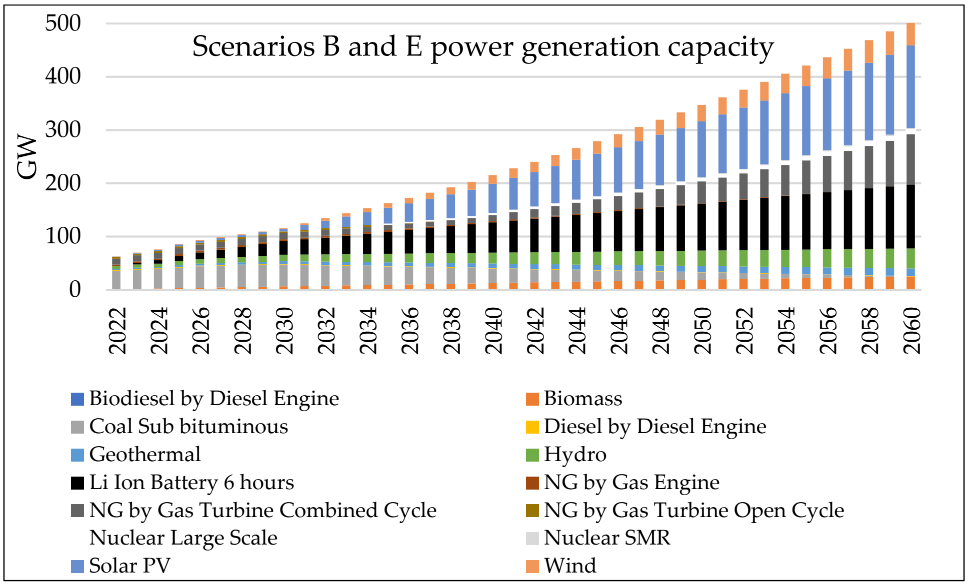

Figure 21. Scenarios B and E of Indonesia's power generation capacity until 2060.

4. Scenario C and F

Scenarios C and F are basically the same, only with differences in NPP technology. These scenarios are based on the retirement of CFPPs in 2060, and the use of NPPs is 10% in 2060. As shown in Figure 22, the total electrical energy produced in 2060 is 1450 TWh, of which 134.7 TWh comes from hydropower (9.3%), coal is 0 TWh (0%), natural gas is 647.7 TWh (44.7%), geothermal power is 113.5 TWh (7.8%), solar PVs is 238.2 TWh (16.4%), wind is 54.4 TWh (3.8%), diesel fuel is 0 TWh (0%), biodiesel is 0 TWh (0%), biomass is 121.3 TWh (8.4%), NPP LRs is 104.7 TWh (7.2%), and NPP SMRs is 35.6 TWh (2.5%). The total electricity generation capacity in 2060 will be 503.3 GW, as shown in Figure 23. The power generation comes from hydropower with 37.5 GW (7.5%), CFPP with 0 GW (0%), natural gas (gas engine, gas turbine open cycle, and gas turbine combined cycle) with

86.1 GW (17.1%), geothermal power with 14.4 (2.9%), solar PVs with 155 GW (30.8%), wind with 45.5 GW (9%), diesel fuel with 0.5 GW (0.1%), biodiesel with 0.5 GW (0.1%), biomass with 24.5 GW (4.9%), NPP LRs with 14.4 GW (2.9%), NPP SMRs with 4.9 GW (1%), and Li-Ion batteries with 120 GW (23.8%).

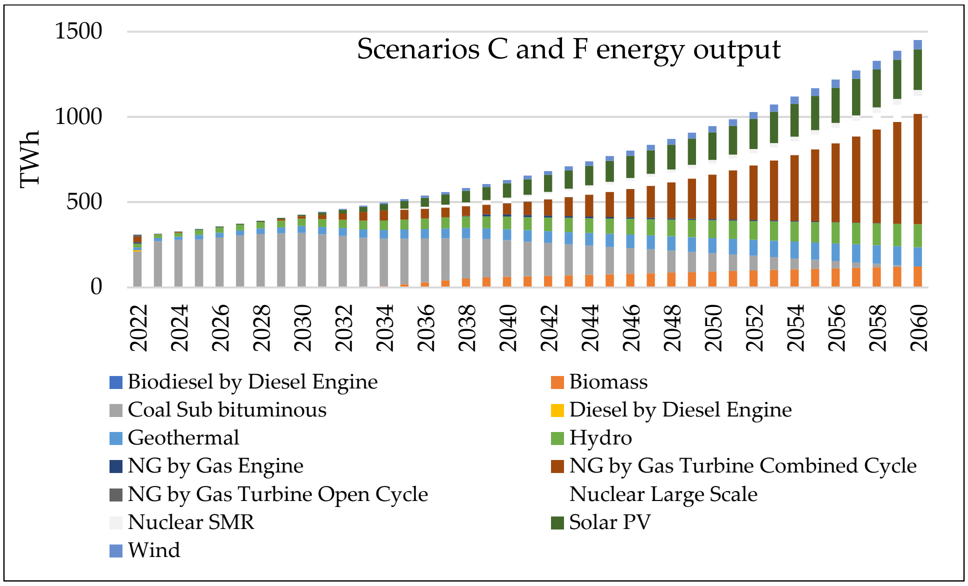

Figure 22. Scenarios C and F of Indonesia's electricity energy production until 2060.

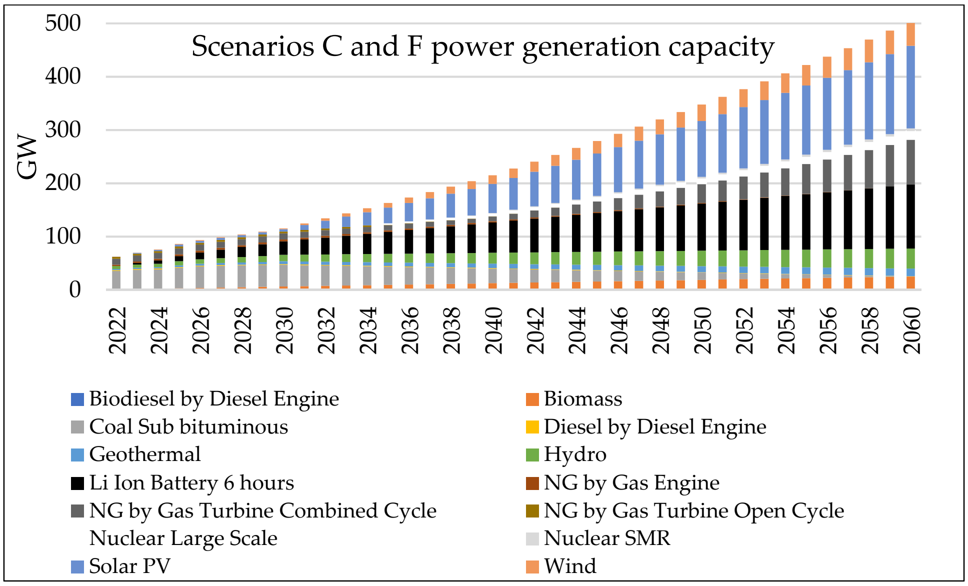

Figure 23. Scenarios C and F of Indonesia's power generation capacity until 2060.

5. Scenarios D and G

Scenarios D and G are basically the same, only with differences in NPP technology. These scenarios are based on the retirement of CFPPs in 2060, and the use of NPPs is 15% in 2060. Figure 24 shows that the total electrical energy produced in 2060 is 1450 TWh, of which 134.7 TWh comes from hydropower (9.3%), coal is 0 TWh (0%), natural gas is 584 TWh (40.3%), geothermal power is 113.5 TWh (7.8%), solar PVs is 238.2 TWh (16.4%), wind is 54.4 TWh (3.8%), diesel fuel is 0 TWh (0%), biodiesel is 0 TWh (0%), biomass is 108.2 TWh (7.5%), NPP LRs is 162.9 TWh (11.2%), and NPP SMRs is 53.8 TWh (3.7%). The total electricity generation capacity in 2060 will be 506.8 GW, as shown at Figure 25. The power generation comes from hydropower with 37.5 GW (7.4%), CFPPs with 0 GW (0%), natural gas (gas engine, gas turbine open cycle, and gas turbine combined cycle) with 79.1 GW (15.6%), geothermal with 14.4 (2.8%), solar PVs with 155 GW (30.6%), wind with 45.5 GW (9%), diesel fuel with 0.5 GW (0.1%), biodiesel with 0.5 GW (0.1%), biomass with 22.4 GW (4.8%), NPP LRs with 22.4 GW (4.4%), NPP SMRs with 7.4 GW (1.5%), and Li-Ion batteries with 120 GW (23.7%).

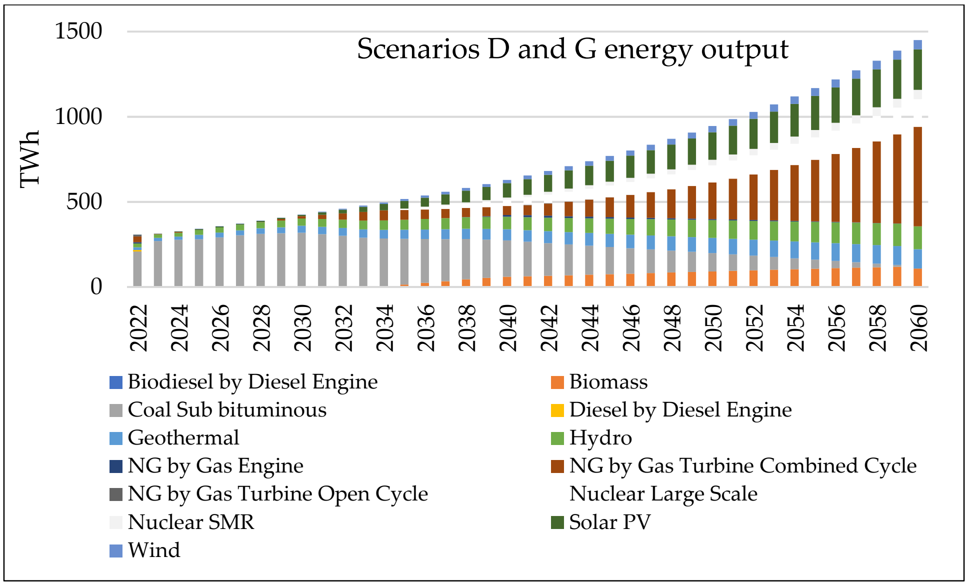

Figure 24. Scenarios D and G of Indonesia's electricity energy production until 2060.

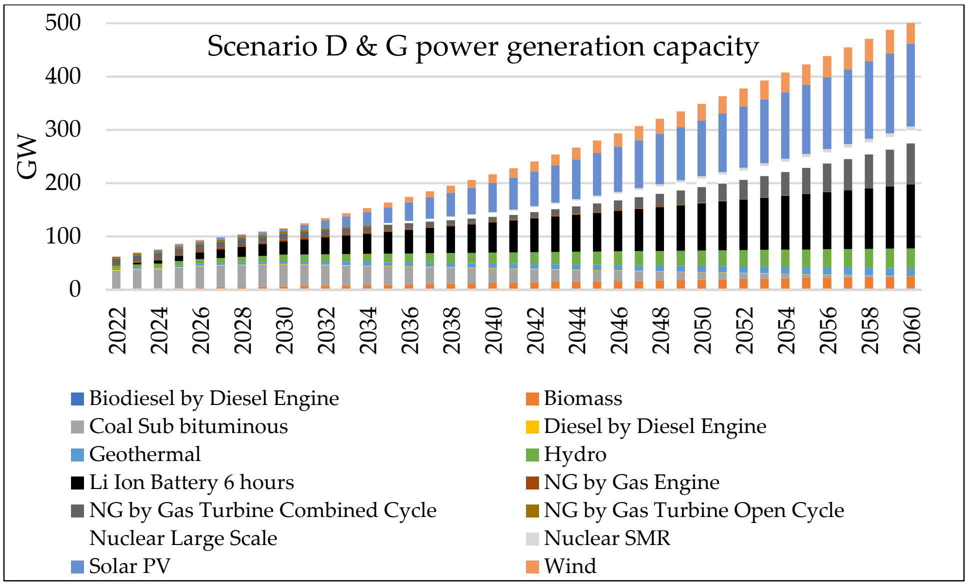

Figure 25. Scenarios D and G of Indonesia's power generation capacity until 2060.

4.4. Analysis of the Opportunity and Challenge of NPPs to Support Net-Zero Emissions

1. CO_2 Emission

Figure 26 shows the production of CO_2 emissions from the various scenarios run. The BaU scenario, which is still dominated by coal, produces the highest CO_2 emissions of 842 million tons in 2060. There is a very significant reduction in CO_2 emissions with the implementation of the retired CFPPs, where CO_2 production in scenarios A to G experiences a decreasing trend. The energy mix in scenario A is dominated by natural gas (54.4%), resulting in emissions of 283 million tons of CO_2 in 2060. In scenarios B and E, the utilization of NPPs is 4.9% and natural gas is 50.3% in the energy mix in 2060. The magnitude of CO_2 emissions in 2060 in these scenarios is 261.6 million tons. The utilization of NPPs of 9.7% of the energy mix in 2060 is in scenarios C and F. In these scenarios, the percentage of natural gas utilization in the energy mix is 44.7%. In 2060, scenarios C and F produce emissions of 232.3 million tons of CO_2. The D and G scenarios utilize NPPs at around 14.9% and natural gas at 40.3% of the energy mix. These scenarios produce 209.4 million tons of CO_2 in 2060. With the limited potential of renewable energy resources in Indonesia, NPPs can be a solution in reducing CO_2 emissions. Renewable energy and NPPs are the main keys to achieving CO_2 emission reductions in the future. Apart from that, the excessive use of natural gas will result in insufficient domestic natural gas production, resulting in the need to use imported natural gas.

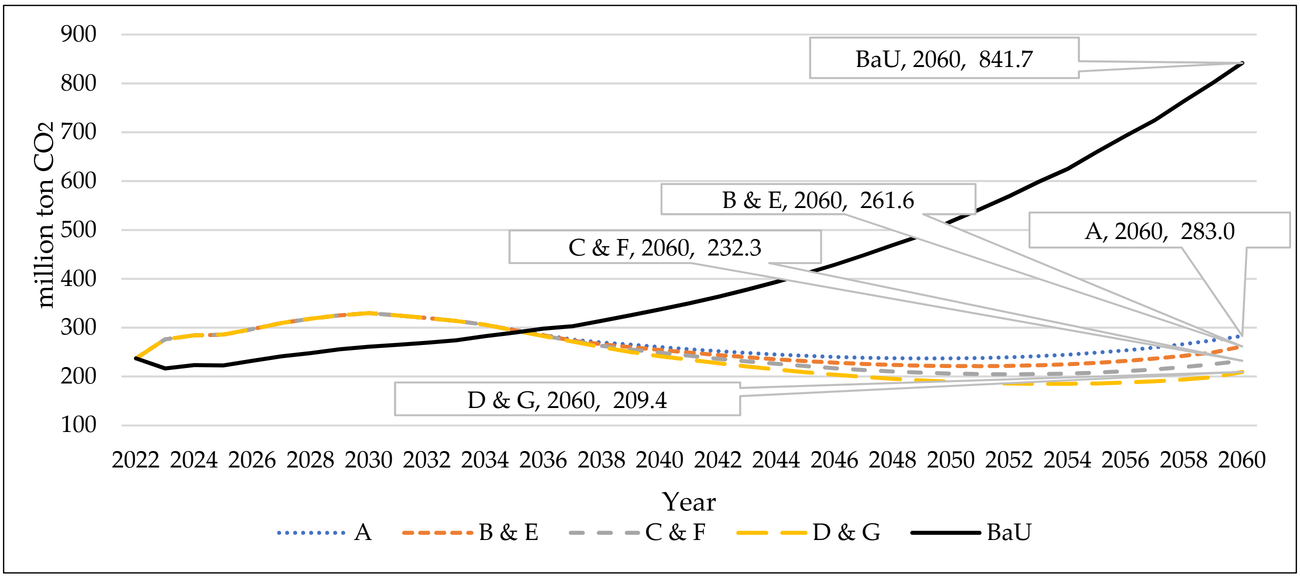

Figure 26. Comparison of CO_2 emission production in various scenarios.

2. Cost of production

Electricity production costs from various scenarios are shown in Figure 27. The BaU scenario, which is dominated by coal, has the lowest production cost of USD 118.8 billion in 2060. Scenarios A to G, which simulate retired CFPPs, have higher production costs than BaU. In scenario A, where the contribution of NPPs is still 0% in the energy mix, production costs are lower than in the scenario that uses NPPs in energy production. Scenario A has a production cost of USD 130.1 billion in 2060. In relation to the use of NPPs, in scenarios B and E, NPPs make up 5% of the energy mix to meet electrical energy production needs. Scenario B, using optimistic costs (typical Korea LRs and the SMR HTR-PM), has a production cost of USD 130.9 billion in 2060. This cost is lower than scenario E, with a conservative cost approach (typical France LRs and the SMR VBER). Scenario E has a production cost of USD 133.0 billion in 2060. Scenarios C and F, which use NPPs at a proportion of 10% in their total electrical energy production, have different production costs. Scenario C, which uses the optimistic NPP approach, has a production cost of USD 131.5 billion in 2060. Meanwhile, scenario F, which uses the conservative NPP approach, has a cost of USD 136.0 billion in 2060. An NPP utilization of 15% is found in the energy mix of scenarios D and G. Scenario D, with the optimistic NPP approach, has an electrical energy production cost of USD 132.5 billion in 2060. Scenario G, with the conservative NPP approach, has an electrical energy cost of USD 139.1 billion in 2060. The increasing use of NPPs in the retired CFPP program will increase the electricity production costs. The relatively more expensive cost of producing electrical energy with NPPs is a challenge in utilizing NPPs in the Indonesian electricity system. The use of NPP technology which has low capital costs (typical Korean LRs) can provide an opportunity to reduce the cost of producing electrical energy using NPPs.

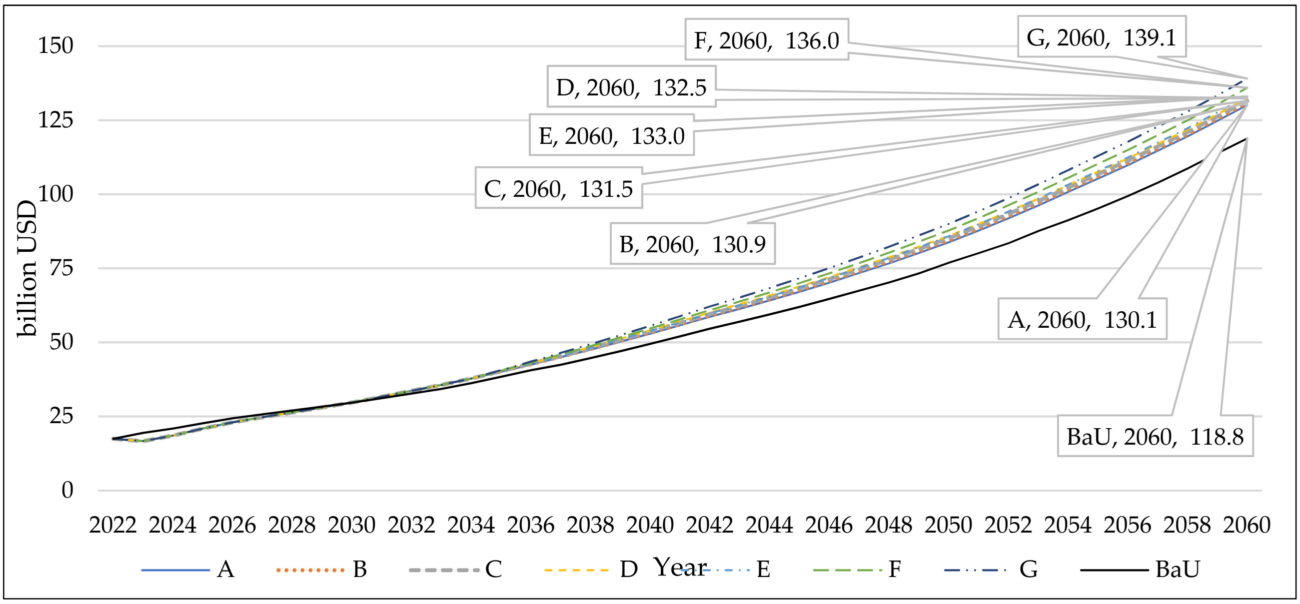

Figure 27. Comparison of cost of production in various scenarios.

3. Cost of investment

Power generation investment costs from various scenarios are shown in Figure 28. The BaU scenario, which is dominated by coal, has the lowest investment cost of USD 500.3 billion in 2060. Scenarios A to G, which simulate retired CFPPs, have higher investment costs than BaU. In scenario A, where the contribution of NPPs is still 0% in the energy mix, the cumulative investment cost required is USD 609.9 billion in 2060. Scenarios B and E use NPPs at a proportion of 5% of the total energy mix to meet electrical energy production needs. Scenario B, using optimistic costs (typical Korea LRs and the SMR HTR-PM), has an investment cost of USD 635.3 billion in 2060. This cost is lower than scenario E with a conservative cost approach (typical France LRs and the SMR VBER), which has an investment cost of USD 655.1 billion in 2060. Scenarios C and F, which use NPPs at a proportion of 10% of their total electrical energy production, have different production costs. Scenario C, which uses the optimistic NPP approach, has an investment cost of USD 656.0 billion in 2060. Meanwhile, scenario F, which uses the conservative NPP approach, has an investment cost of USD 700.7 billion in 2060. An NPP utilization of 15% is found in the energy mix of scenarios D and G. Scenario D, with the optimistic NPP approach, has an investment cost of USD 683.3 billion in 2060. Scenario G, with the conservative NPP approach, has an investment cost of USD 749.3 billion in 2060. Increasing the use of NPPs will increase investment costs in these various scenarios.

The BaU scenario still uses CFPPs as the dominant type of power generation until 2060 and has a 12.3% VRE penetration. In scenarios A–G, CFPPs have been retired in 2060. The use of NPPs in scenario A is 0%, and VRE is about 20.2%. There is a difference in investment costs in the two scenarios. The investment cost in scenario A is USD 109.66 billion, 22% higher than in the BaU scenario. Figure 29 shows the difference in investment costs for the BaU scenario compared to scenario A from the aspect of power plant technology. It can be seen that the investment cost for developing CFPPs in the BaU scenario is much greater than in scenario A. Battery storage (Li-Ion) is one of the causes of the high investment cost in scenario A.

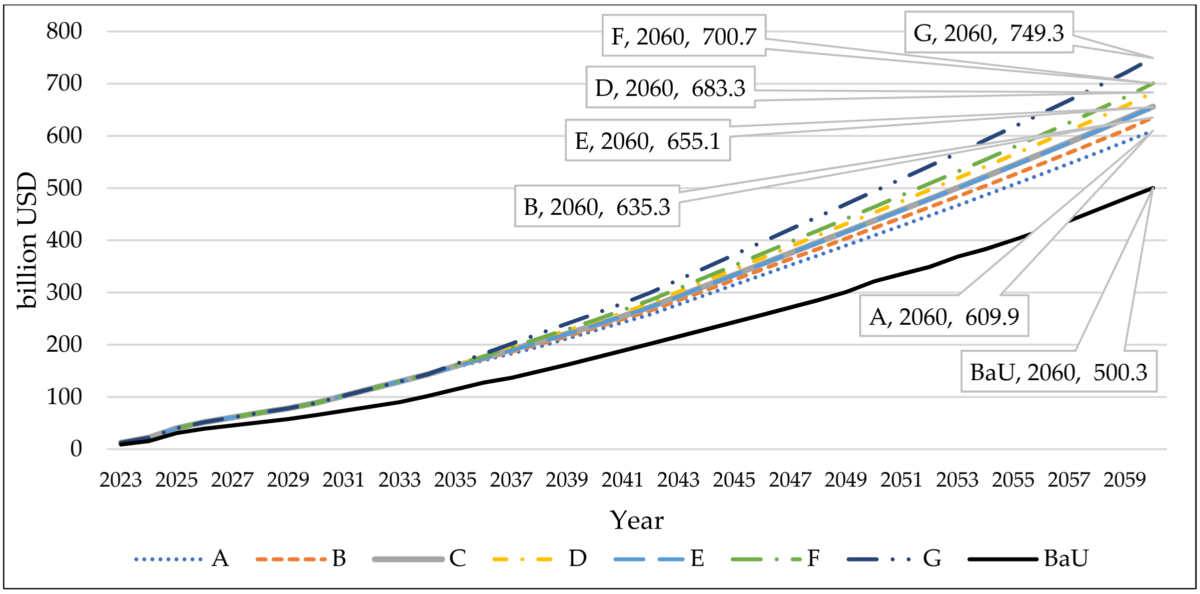

Figure 28. Comparison of cost of investment (cumulative) in various scenarios.

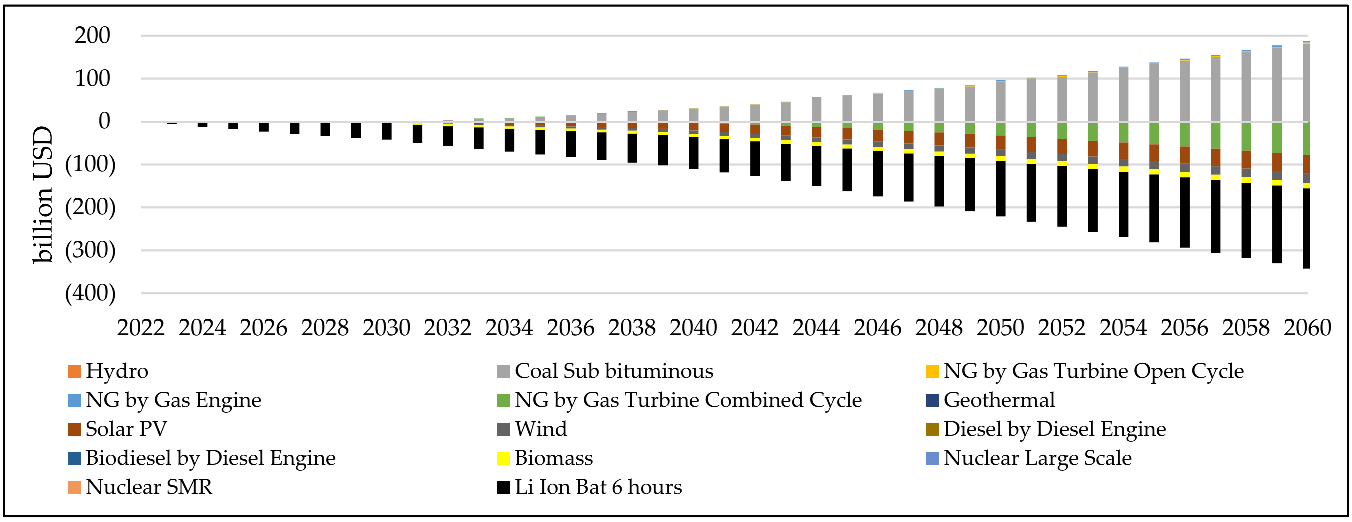

Figure 29. Difference in investment cost between scenario BaU and A.

5. Conclusions

Indonesia's national position regarding the NPP program is still in phase 1, namely the considering phase. Legally, Indonesia has not committed to utilizing NPPs in its electricity system. This is reflected in the absence of a commitment to utilize NPPs in laws, the National Development Plan, and energy policies in Indonesia. The absence of a NEPIO in Indonesia means that the supporting infrastructure for the nuclear program is incomplete. Structurally, the NEPIO can be led by the highest leader (Prime Minister/President) or an authorized minister, such as the Minister of Energy. Locations that have a low seismic, tsunamic, and volcanic risk as candidate locations for NPPs are the east coast of Sumatra, Bangka Belitung, West Kalimantan, Central Kalimantan, South Kalimantan, parts of East Kalimantan, and Merauke Papua. Using LEAP software, a simulation of the utilization of NPPs was carried out with a general scenario in the form of BaU and retired CFPPs in 2060. With the retired CFPPs, scenarios of utilization of NPPs in the energy mix were analyzed: A (0% NPPs), B (5% NPPs, optimistic cost), C (10% NPPs, optimistic cost), D (15% NPPs, optimistic cost), E (5% NPPs, conservative cost), F (10% NPPs, conservative cost), and G

(15% NPPs, conservative cost). Optimistic NPPs use typical Korean LRs and the SMR HTR-PM. Meanwhile, conservative NPPs use typical France LRs and the SMR VBER-300. With the limited potential for renewable energy in Indonesia, such as hydro, geothermal, solar, and wind power, NPPs have the opportunity to fulfill electrical energy needs and reduce CO_2 emissions. The challenge of using NPPs is the increasing production and investment costs that come along with the increase in the use of NPPs in the electricity system.

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Abbreviations

BATAN	National Energy Atomic Agency, now part of BRIN (national research and innovation agency)
BaU	Business as Usual
BWR	Boiling Water Reactor
GHG	Greenhouse gasses
IAEA	International Atomic Energy Agency
INIR	Integrated Nuclear Infrastructure Review
KEN	National Energy Policy
LEAP	Low emissions analysis platform
LRs	Large Reactor
NEPIO	The Nuclear Energy Program Implementation Organization
NPPs	Nuclear power plants
O & M	Operation and maintenance
PLN	Perusahaan Listrik Negara (State Electricity Company of Indonesia)
PWR	Pressurized Water Reactor
RUEN	National Energy Plan
RUKN	National Electricity Master Plan
RUPTL	National Electricity Plan
SMRs	Small Modular Reactors
VRE	Variable renewable energy

Appendix A Leap Model Parameter

Table A1. Historical demand data in TWh.

Demand	2018	2019	2020	2021	2022
Household	97.83	103.73	112.16	115.37	116.10
Business	44.03	46.91	42.82	44.40	50.53
Public	15.81	17.00	16.37	16.92	18.65
Industry	76.95	77.89	72.24	80.90	88.5
Total	234.62	245.53	243.59	257.59	273.76

Table A2. Additional power generation capacity (MW) [60].

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydro	207	409	376	1627	470	721	885	1061	856
Coal sub-bituminous	2444	1542	350	1891	2260	624	-	20	-
Natural gas by gas turbine open cycle	-	-	-	-	-	-	-	-	-
Natural gas by gas engine	543	316	240	370	80	95	-	10	70
Natural gas by gas turbine combined cycle	1279	-	-	-	80	-	-	-	100
Geothermal	108	190	141	870	290	123	450	240	808
Solar PV	287	1308	624	1631	127	148	165	172	157
Wind	45	121	528	376	90	-	15	-	300
Diesel by diesel engine	-	-	-	-	-	-	-	-	-
Biodiesel by diesel engine	-	-	-	-	-	-	-	-	-
Biomass by CFPP	-	-	-	-	-	-	-	-	-
Total	4913	3886	2259	6765	3397	1711	1515	1503	2291

Table A3. Fuel price.

Fuel	Unit	2019	2020	2021	2022	2030	2040	2050	2060
Oil	USD/barrel	80.21	61.10	83.11	139.09	110.00	105.00	102.00	100.00
Coal sub-bituminous	USD/ton	51.07	61.13	50.93	57.67	60.00	63.00	65.00	68.00
Biomass	USD/ton	71.49	85.59	71.31	80.73	84.00	88.20	91.00	95.20
UO_2	USD/kWh	0.007	0.007	0.007	0.007	0.007	0.008	0.008	0.008
Biodiesel	USD/barrel	74.19	84.79	127.19	137.79	120.00	110.00	100.00	95.00
Natural gas	USD/MMBTU	7.70	6.78	5.87	7.45	8.00	9.00	10.00	11.00

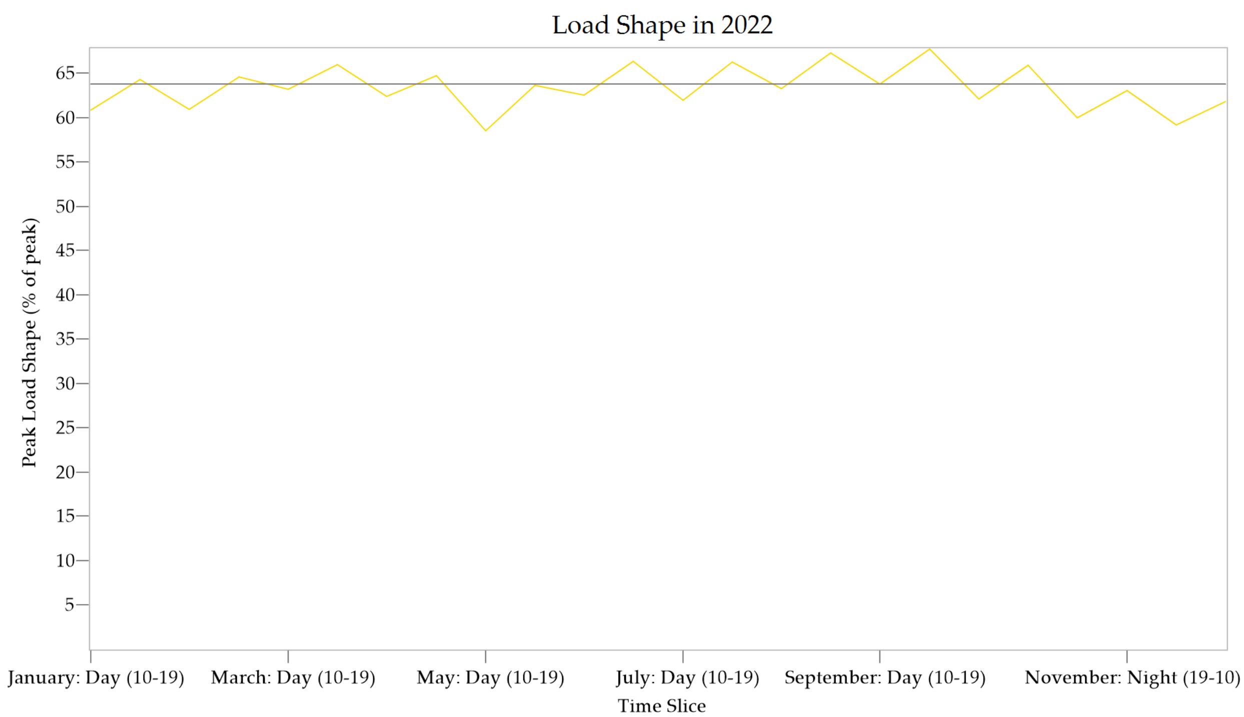

Figure A1. Load shape [150].

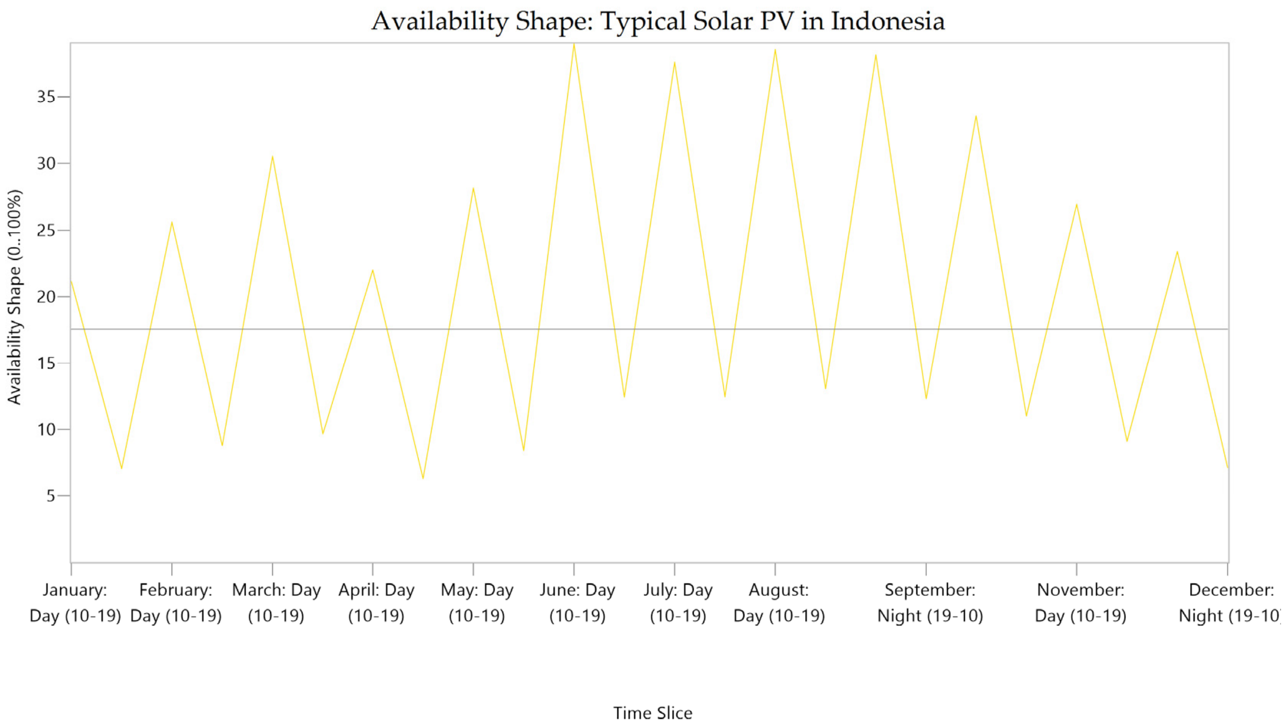

Figure A2. Solar availability curve [155].

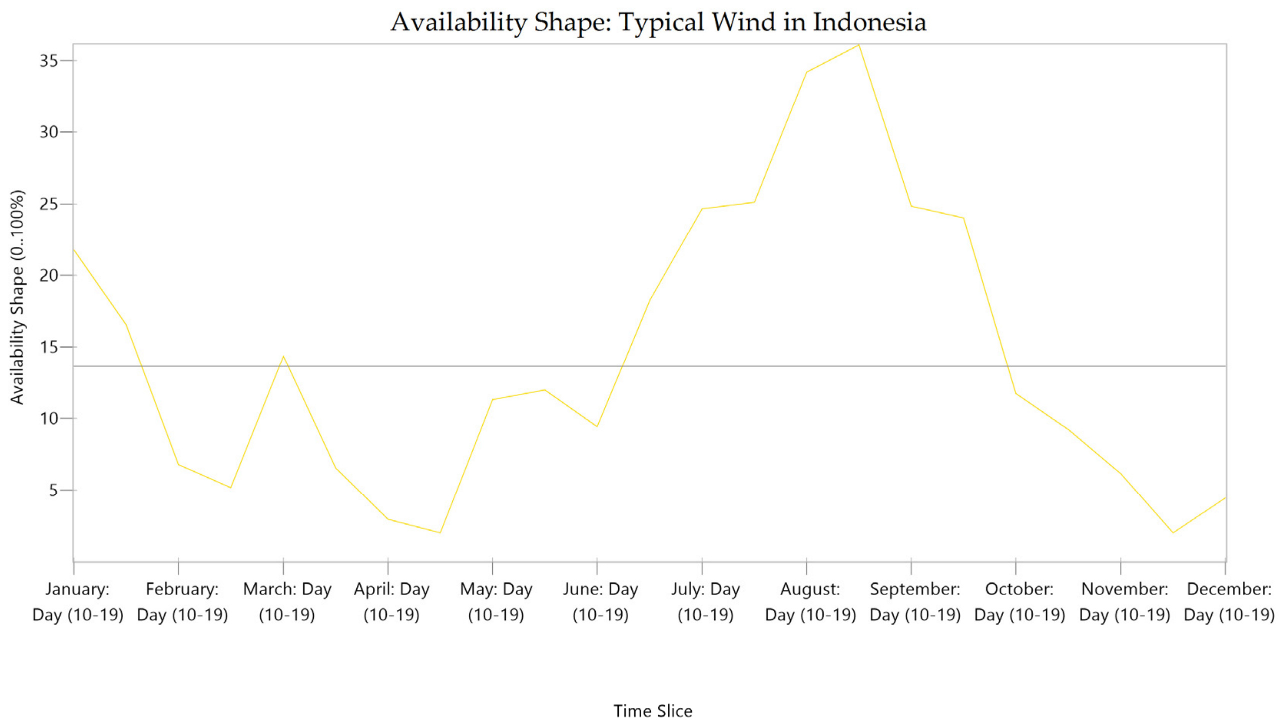

Figure A3. Wind availability curve [156].

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