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The Role of Nuclear Power Plants in Indonesia towards Net Zero Emissions (NZE) in 2060 with a Multi Regions Approach

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Abstract: The Indonesian government plans an energy transition roadmap toward NZE until 2060. The power sector will gradually replace all fossil power plants with new and renewable energy (NRE) power plants. Using an energy optimization model Low Emission Analysis Platform (LEAP), we project the demand and supply of electricity by 2060. This energy model will divide Indonesia into six regions: Sumatra, Jamali (Java, Madura, Bali), Kalimantan, Sulawesi, Nusa Tenggara, and Maluku, Papua. The scenarios used are NZE1, NZE2, and NZE3. In the NZE1 scenario, there is no interconnection grid between regions. In the NZE2 scenario, there is an interconnection between the Sumatra and Jamali regions, while the NZE3 scenario accommodates the interconnection of the Jamali, Sumatra, and Kalimantan regions. Among the NREs planned in the NZE roadmap is nuclear power plants (NPPs), which could be an alternative solution to coal-fired power plants as a baseload. Based on the forecast results, the installed capacity of nuclear power plants in Indonesia's energy mix 2060 under NZE1, NZE2, and NZE3 scenarios will be 45GW, 25GW, and 25GW, respectively. Due to the lack of interconnections between regions, the NPP must be operational by 2040. Then, the presence of inter-regional connections could delay nuclear power plant operations until 2045. The NZE3 scenario gives the best option toward Net Zero Emissions, and NPPs will contribute 3,77% in the power generation mix in 2060.

Keywords: nuclear power plant; renewable energy; net zero emissions; multi regions

1. Introduction

With abundant fossil energy resources like coal, oil, and gas, Indonesia has long depended on fossil-fueled power plants. According to PLN statistics[1)], the current installed capacity and electricity production shares account for 84% and 82% of total power generation, respectively. The rest are taken by renewable power plants, which have shown promising potential in Indonesia, such as research on geothermal energy [2)], bioenergy[3)], biofuel[4)], solar radiation[5)], wind energy[6)], and hydropower[7)]. Among these renewable energies, the role of biogas, municipal waste, wind, and solar are still tiny.

Climate Transparency reported that the power sector contributed 35% of overall GHG emissions in 2020. It was related to GHG emissions in the power sector of 0.72 tons of CO_2 eq./MWh, higher than the G20 countries' average of 0.43 tons of CO_2 eq./MWh[8)]. Coal power plants contribute the largest GHG (greenhouse gas) emissions, reaching 44% of global CO_2 emissions[9)]. Five priority emission categories GHG (CO_2, $PM_{2.5}$, SO_2, NO_x, Hg) released into the air along the coal power plant supply chain[10)]. CO_2 production from coal power plants has started in the mining process through land clearing (deforestation), mining operations, coal transportation, and power plant operations[10)]. The percentage of CO_2 in the mining process due to land clearing reaches 40.25 - 48.7%, and mining operations reach 51.3 – 59.75%; it varies by region[11)].

In the United Nations Climate Change Conference of the Parties (COP) 26 in Glasgow, Indonesia pledged to contribute to the global Net Zero Emissions (NZE)[12)]. It is meant to keep the global average temperature rise below 2 degrees and pursue a target of 1.5 degrees Celsius above pre-industrial levels at the end of this century[13)]. Moreover, Indonesia is planning to phase out gradually its coal-fired and other fossil-fueled power plants by 2060[12,14)].

The energy transition in the power sector from fossil fuels to renewable energy (RE) will change the power plant mix and must be studied carefully[15)]. There are already several studies to assess the optimal power plant technology mix to mitigate global climate change. Luderer et al. revealed that NPPs could contribute to global NZE if all fossil power plants were phased out and no carbon capture and storage (CCS) technologies were used. Although the adoption of NPPs is not as high as solar and wind, nuclear can grow at the median rate of 5% per year during 2020 – 2030[16]. Another study by Ordonez et al. shows that by introducing carbon pricing and cost reduction for renewable energy, RE power plants would dominate the projection of Indonesian power supply in 2040, but there are no nuclear[17]. Indonesia's Institute for Essential Services Reform (IESR) regularly published Indonesia energy outlooks. In one of the scenarios, the role of RE power plants like solar PV will reach about 88% of total power capacities in 2050. Surprisingly, there are no wind power plants in the projection results. In this study, NPPs are also not selected in the resulting power generation mix[18]. The most interesting is the results from International Energy Agency (IEA) special report on the net zero emission roadmap for the global energy sector by 2050. This report predicted that solar, wind, and hydro will contribute to about 80% of all global electricity generation in 2050. Then, it is followed by nuclear, which has a share of about 7.5%. Fossil fuels with carbon capture, utilization, and storage (CCUS) also become part of the roadmap with a share of 2.5%[19].

Nuclear energy-related activity in Indonesia started in 1954 when the State Committee for the Investigation of Radioactivity was formed to observe the possibility of radioactive fall-out from nuclear weapons tests in the Pacific Ocean in the Indonesian Territory. Then, in the early 1960s, the first Indonesian nuclear research reactor, the TRIGA Mark II facility in Bandung, was constructed. Followed by the development of the Kartini research reactor in Yogyakarta, which started its operation in 1979, and the 30 MW multipurpose research reactor in Serpong Nuclear Complex, which came into operation in 1987[20]. Before the 1990s, all these reactors were in operation under the direction of the National Energy Atomic Agency (BATAN), with the Bandung reactor, the Kartini Yogyakarta research reactor, and the Serpong research reactor having maximum fuel burnups of 50%, 10%, and 59%, respectively21). However, until now, Indonesia does not have a nuclear power plant, although nuclear power plants (NPPs) have started to be considered a green energy option in regional development plans around 2010[21].

Nuclear energy has only ever been used in Indonesia for medical[22,23], agricultural[24–26], food radiation[27], and technological research[28–30]. Indonesian areas that are suitable for nuclear power have undergone extensive feasibility studies. Since 1974, potential sites for the Java Madura Bali grid have been prepared while adhering to international and national standards; as a result, 14 regions have been suggested. During the 1980–1983 Batan–NIRA (Nuclear Italiana Reacttori Avancatti) Site Survey feasibility study, five areas were chosen, with the Muria Area receiving the top ranking. New Japan Engineering Consultants (NEWJEC Inc.) continued the research in 1993 and came to three suitable sites in the Muria Area, with the Ujung Lemahabang Site ranking first. This research included projections of electricity demand and supply in Java and Bali that NPPs would meet[31]. In 2009, research on nuclear use in Bangka-Belitung was conducted by BATAN[32], resulting in an NPP with a 10 GWe capacity that might be built by combining four NPP reactors at Sebagin Village Coast in South Bangka and six NPP reactors at Tanjungular in West Bangka's Muntok. Other research was conducted in addition to the site feasibility study, such as Indonesia's spent fuel storage safety [33–35], Small Modular Reactor SMR[36], and floating NPPs[37].

The energy policies in Indonesia always put the construction of nuclear power plants (NPP) as the last priority[38]. Public approval, high capital cost, political condition, government policy, financial, long construction time concerns, and suitable locations continue to be barriers to constructing nuclear power facilities[39]. The public views nuclear plants as dangerous, explosive, hazardous, and radiation poses a health risk since they are uninformed of their advantages over other electrical energy sources[20,40]. NPPs have the highest capacity factor (CF) among the other power plants. NPPs operate at full capacity for more than 92% of the year. That is about twice as much as natural gas and coal units and nearly three times as much as wind and solar plants[41]. Nuclear power plants could replace coal-fired power plants as baseload power plants. Moreover, NPPs have the advantage of producing negligible amounts of CO_2 emissions when considering the entire life cycle (less than 15 g of CO_2 equivalent (g CO_2 -eq) per kilowatt-hour (kWh)), as well as hydro and wind power plants[13]. These make NPPs an attractive solution to be one of the options in Indonesia's power capacity expansion plan to reduce GHG emissions from fossil-fueled power plants and the solution of any renewable energy limitations such as intermittency in the wind and solar power plant, also limited locations for hydropower and geothermal power[42]. Ryota Roneda investigates that many countries are competing to carry out R&D for the development of Nuclear Power Plants, and the USA is still the leader in terms of intellectual property (IP), reaching 40% of global IP in Nuclear Fusion Technology.[42]

Based on the geographical distribution of NRE potential, the prospect of NPPs in the energy transition roadmap towards NZE in Indonesia's power sector has not been explored thoroughly. Even though the existence of the NPP will strengthen National Energy Security, i.e., able to secure sufficient energy for the civil, economic, industrial, and environmental sectors[43]. The key to the survival of a country during intense natural resource competition is energy supply and demand. So, energy security is very important in overcoming the dilemma of economic growth, environmental preservation, and resource security[44].

This paper investigates the role of NPPs in Indonesia's power generation mix towards NZE using LEAP software.

When it comes to modeling energy systems, LEAP is a frequently employed tool, and one of its many strengths is its capacity to combine energy estimates with environmental implications[45]. Numerous studies have been done using LEAP to examine energy estimates in many nations, including Pakistan[46], Brazil[47], China[48], and Malaysia[49]. In Indonesia, LEAP has been used to construct several projection models. LEAP forecasts energy, price, and CO2 emissions for Java-Bali power plant capacity growth scenarios from 2016 and 2050, which accounts for the renewable energy mix target. The findings demonstrate that solar photovoltaic (solar PV) and wind energy are competitive with other renewable energy[50]. Using a scenario design that embraces PLN's RUPTL and greenhouse gas reduction targets, LEAP has been used to forecast the planning level of electricity demand in West Java[51] and the best cost path for developing the electricity sector in Sumatera[52]. This research will forecast and assess the potential capacity and energy output of NPPs to aid Indonesia in achieving its NZE targets by 2060. The deployment of NPPs and its effects on system costs overall, and CO2 emissions are also examined in this research for each defined scenario.

2. Methodology

We developed a supply-demand model in electricity and implemented it in the Low Emission Analysis Platform (LEAP) model[53]. LEAP can perform demand modeling with bottom-up and top-down approaches and combine those two approaches. On the supply side, LEAP supports accounting, simulation methodologies, and optimization modeling capabilities. LEAP also supports multi-regional analyses and inter-regional trade[54]. The structure and calculation flow of the LEAP model can be seen in **Figure 1**.

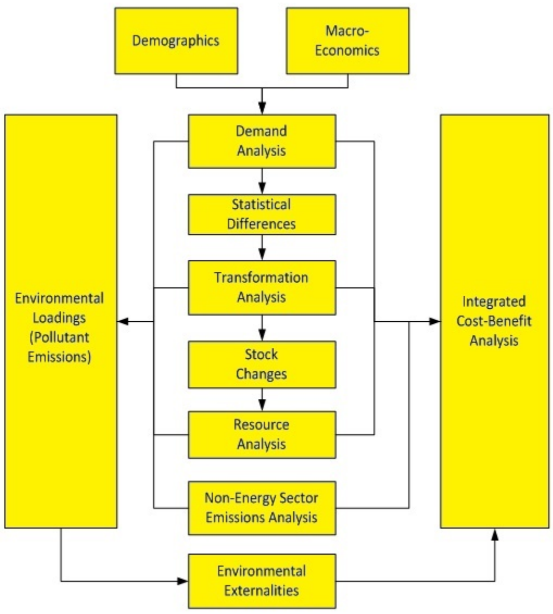


Fig. 1: LEAP structure and calculation flow

This study applies an end-use forecasting method to project electricity demand. We divided Indonesia into six regions: Sumatra, Jawa Madura Bali (Jamali), Kalimantan, Sulawesi, Nusa Tenggara, and Maluku Papua. By utilizing a multi-regional approach, this paper will be able to assess the demand and supply more precisely in each region based on the conditions of each region. The results will then be compared to previous studies, most of which used a national approach or single region[19,50–52,55]. We computed electricity demand in each region's economic sectors, including industries, transportation, commercials, and households. The electricity demand for each sector in each region can be calculated using the following equations[53]:

$$E_{ic} = A_{ic} \times I \quad (1)$$

$$E_h = A_h \times \frac{U}{Eff} \quad (2)$$

$$E_t = S \times \frac{D}{C} \quad (3)$$

Where E_{ic} is the electricity demand for industries or commercials, E_h is the electricity demand for households, E_t is the electricity demand for transport, A_{ic} is the activity level of industries or commercials, A_h is the activity level of households, S is the number of vehicles, I is final energy intensity of industries or commercials, U is useful energy intensity of households, D is vehicle mileage, Eff is appliance efficiency, and C is specific energy consumption.

Table 1. Average growth rate assumptions of (a) population and (b) gross regional domestic products (GRDP) by region. (2010 constant price)

(a)

Region	2020 (million)	2060 (million)	Average growth rate 2021 – 2060
Sumatra	58.6	80.0	0.79%
Jamali	155.9	179.5	0.37%
Kalimantan	15.6	21.7	0.69%
Sulawesi	19.9	24.4	0.53%
Nusa Tenggara	10.6	15.0	0.87%
Maluku Papua	8.6	11.2	0.90%

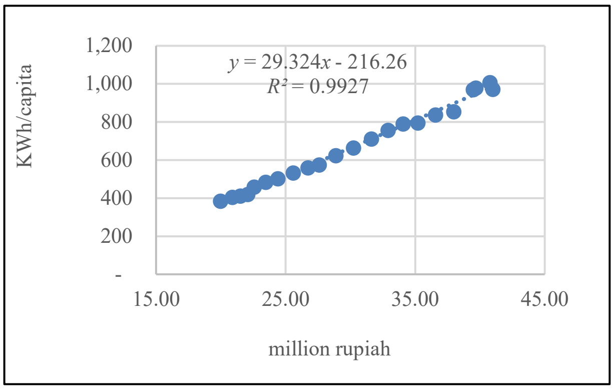
(b)

Region	2020 (trillion Rp)	2060 (trillion Rp)	Average growth rate 2021 – 2060
Sumatra	2,303	15,248	5.25%
Jamali	6,513	50,552	5.61%
Kalimantan	898	6,215	5.33%
Sulawesi	704	7,873	6.66%
Nusa Tenggara	162	1,160	5.43%
Maluku Papua	258	1,823	5.64%

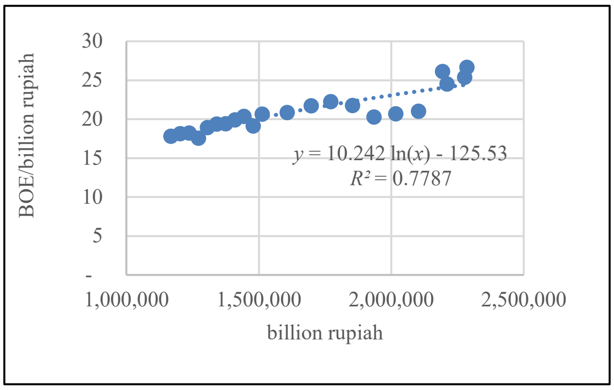
The data employed in this study is derived from various official institutional publications, constituting secondary data. To get the activity level of the sectors, we need assumptions for socio-economic indicator projections. For these, we performed our analysis based on the Agency for Indonesia Statistic (BPS) publications[56,57] and a non-published assessment of the Ministry of National Development Planning/National Development Planning Agency (Bappenas). The results of our analysis are presented in **Table 1**.

Besides the activity levels, we must project final energy intensities using historical electricity consumption. These can get from the Handbook of Energy and Economic Statistics of Indonesia (HEESI) [58] and BPS statistics for the historical gross domestic product (GDP), such as the GDP of industry and commercial.

Growth in economic and per capita energy consumption will increase general energy per capita, resulting in a decrease in energy intensity as the result of implementing energy-saving technologies. The GDP growth rate is faster than the energy consumption growth rate, and the population growth rate is faster than the energy consumption growth rate.[59].



(a)



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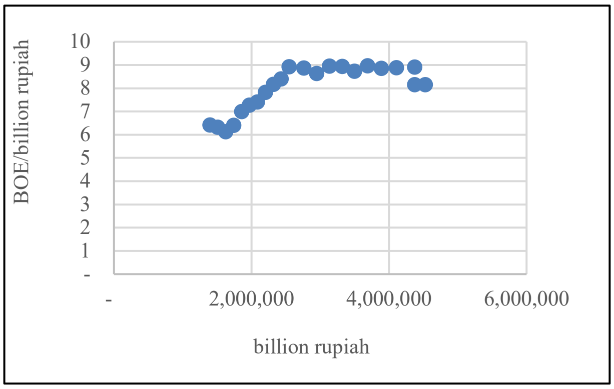


(c)

Fig. 2: (a) Electricity consumption per capita (KWh/capita) vs. income per capita (million rupiahs). (b) Industrial electricity intensity (BOE/billion rupiahs) vs. GDP of Industries (billion rupiah). (c) Commercial electricity intensity (BOE/billion rupiahs) vs. GDP of Commercials (billion rupiahs). (2010 constant price)

We use the past twenty years' GDP and electricity per capita data from 2000 until 2021 to get the historical energy intensities. We assume no significant regional gap in energy technology implementation in all sectors. Then, we can have the same energy intensity projection trends across all regions.

We have found interesting correlations between electricity per capita and GDP per capita, as well as between electricity intensity and sectoral GDP, as shown in **Figure 2**. We notice a perfect linear correlation between electricity consumption per capita and income per capita, as the value of R^2 is close to one. For the industrial sector, the correlation between industrial electricity intensity and GDP is non-linear and considered a strong correlation since the value of its R^2 is higher than 0.75[60]. Conversely, the commercial sector has a different correlation. The commercial electricity intensity seems no longer sensitive to the increasing commercial sector GDP. It tends to be constant.

We approach the number of vehicles for the transport sector using the stock analysis method. The adoption of new electric vehicle technology is assumed to follow an S-curve[61]. Using Gaikindo vehicle sales data trend[62] and BPS statistics for the vehicle stock data, we can forecast the vehicle stock, particularly road transport, by 2060. **Figure 3** shows the projection result.

All passenger cars and motorcycles will already be electric vehicles by 2060. The specific fuel consumption of electric cars, buses, trucks, and motorcycles is assumed to be one-third of conventional or internal combustion engine vehicles with the same mileage (see **Table 2**)[63].

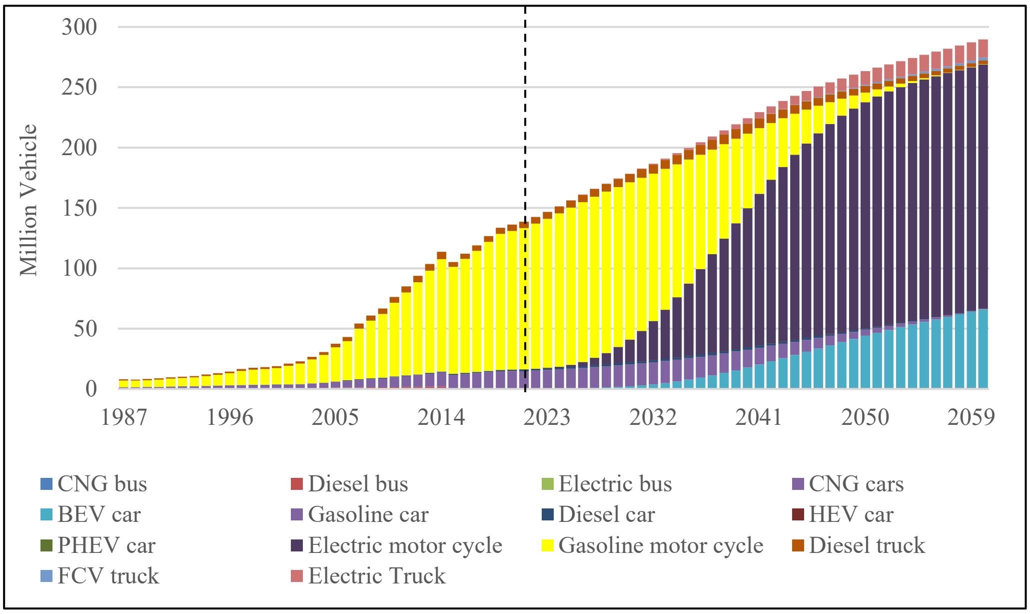


Fig. 3: Total projection of vehicle stock in all regions

Table 2. Specific fuel consumption and mileage of electric vehicles

Vehicle type	Specific fuel consumption	Mileage
Electric car	88.9 MJ/100 km	14,000 km
Electric bus	231.2 MJ/100 km	25,000 km
Electric truck	281.8 MJ/100 km	25,000 km
Electric motorcycle	31.1 MJ/100 km	8,000 km

Historical electricity consumption in all regions can be found in the Directorate General of Electricity, Ministry of Energy and Mineral Resources (MEMR) statistics[64]. The domestic power supply will always meet all regional electricity demands. Neither import nor export of electricity from and to abroad respectively is allowed. As mentioned before, we use the LEAP model to analyze the electricity supply demand. We can perform the least cost optimization in the power sector using LEAP with the support of optimization tools called Next Energy Modeling system for Optimization (NEMO)[65]. The initial development of NEMO using an Open-Source Energy Modelling System (OSeMOSYS). The objective of least-cost optimization is to have the smallest present value (NPV) total cost of a power generation system to meet a given electricity demand which the following equation can express[17) 66)]:

$$\min Total\ Discounted\ Cost =$$

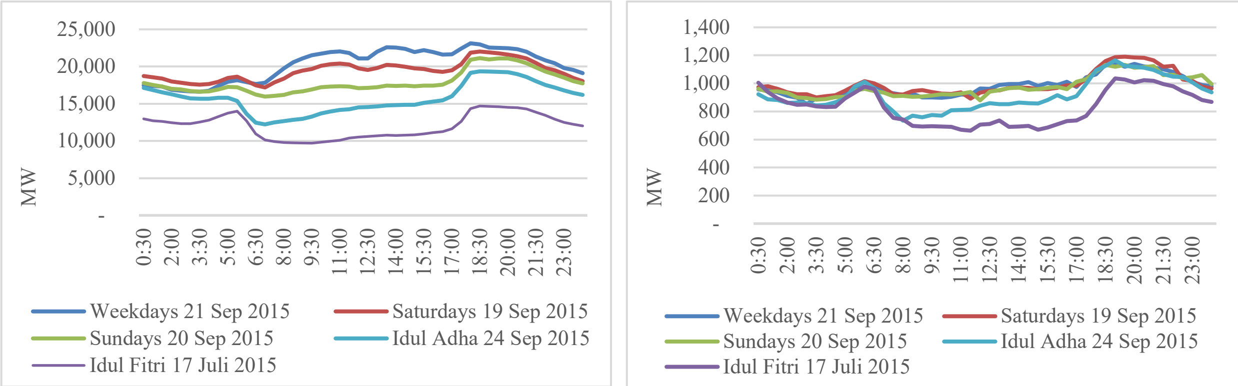
$$\min\left\{\sum_r \sum_y \left[\frac{1}{(1+d)^{y-y_b}} \sum_{PGT} \left[\begin{array}{l} annualized\ capital\ costs_{y,r} + fixed\ costs_y \times capacity_{PGT,y,r} \\ + operational\ costs_y \times \sum_t generation_{PGT,y,t,r} \end{array}\right]\right]\right\} \quad (4)$$

Where r is the region, y is the year, yb is the base year, PGT is power generation technology, t is the time slice, and d is the discount rate.

The capital cost, fixed operations and maintenance (O&M) cost, variable O&M cost, fuel cost, capacity factor, and efficiency for each power generation technology such as coal, gas, oil, hydro, geothermal, solar, wind, biomass, biogas, municipal waste, tidal, nuclear and battery storage are taken from Ministry of Energy and Mineral Resources (MEMR) publication (see **Table 3**)[67].

Regarding the time slice in the equation, not all power plants operate 24 hours a day. They operate according to a load curve: base, intermediate, and peak load. Since PLN divided the load curve into 2 x 8760 half-hour time slices, running the model using that large amount of time slices will not be possible. Therefore, we split one year into 2 x 2 x 24 or 96-time slices. It means the typical model load curve is differed by wet and dry seasons, weekdays and weekends, and 24 hours a day. **Figures 4** show the typical PLN load curves for Jamali and Sumatra regions. We assume that the load curves of other regions are similar to Sumatra's.

Unlike fossil energy, RE is regarded as a local energy resource that cannot be transported, particularly geothermal, hydro, solar, and wind, except uranium and biomass. We need to know the potential technical resources of RE in each region instead of using, for example, Global Solar Atlas[68] and Global Wind Atlas[69] data. MEMR[64] has calculated the maximum technical capacities of NRE power plants that can be built in a specific region (see **Table 4**).



(a) (b)

Fig. 4: (a) Load Curve of Jamali. (b) Load Curve of Sumatra

Table 3. Power Plant (PP) Costs

Power Plant	Capital cost (thousand US$/MW)			Fixed OM cost (thousand US$/MW)			Variable OM cost (USD/MWh)		
	2019	2030	2050	2019	2030	2050	2019	2030	2050
Coal Steam	1,400	1,360	1,320	41.20	39.90	38.70	0.12	0.12	0.11
Gas Steam	1,400	1,400	1,400	41.20	39.90	38.70	0.12	0.12	0.11
Oil Steam	1,400	1,400	1,400	41.20	39.90	38.70	0.12	0.12	0.11
Combined Cycle	750	710	660	23.30	22.50	21.80	0.13	0.13	0.12
Gas Turbine	770	730	680	23.30	22.50	21.80	0.13	0.13	0.12
Gas Engine	800	800	780	8.00	8.00	7.80	6.40	6.00	5.80
Diesel Engine	800	800	780	8.00	8.00	7.80	6.40	6.00	5.80
Hydro	2,000	2,000	2,000	37.70	35.80	33.60	0.65	0.62	0.58
Mini/Micro Hydro	2,600	2,600	2,600	53.00	50.40	47.20	0.50	0.48	0.45
Hydro Pump Storage	750	750	750	37.70	35.80	33.60	1.30	1.30	1.30
Geothermal	3,500	3,200	2,900	18.00	16.70	15.20	0.25	0.23	0.21
Biomass	1,700	1,600	1,400	47.60	43.80	37.10	3.00	2.80	2.40
Biogas	2,800	2,600	2,200	97.00	89.20	77.60	0.11	0.10	0.10
Municipal Solid Waste	2,500	2,300	2,000	125.00	125.00	125.00	3.00	3.00	3.00
Solar	1,200	1,000	800	15.00	12.50	10.50	-	-	-
Wind	1,600	1,400	1,200	60.00	55.00	44.00	-	-	-
Tidal	5,000	3,350	2,000	150.00	150.00	150.00	-	-	-
Nuclear	5,000	5,000	4,000	101.00	80.00	70.00	0.31	0.31	0.31
Battery Storage	1,400	1,000	800	37.00	30.00	15.00	-	-	-

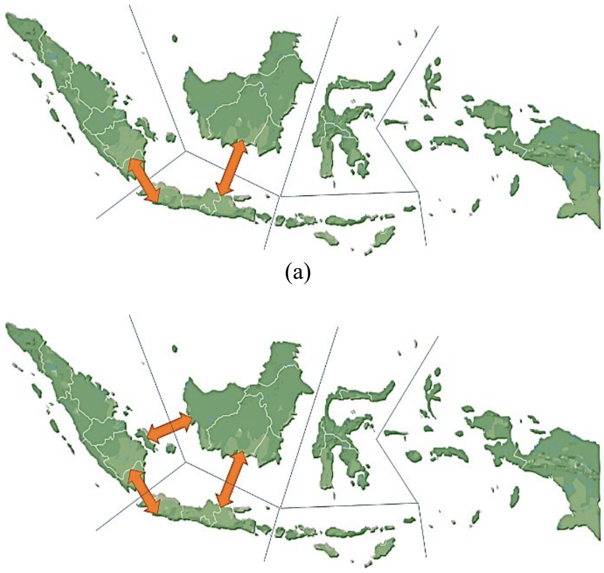
Table 4. Maximum potential generating capacity of RE by region (unit of GWe)

Region	Solar	Hydro	Bioenergy	Wind	Geothermal	Tidal	Uranium (thousand tons)
Sumatra	1,173.70	6.75	27.88	11.24	9.52	23.89	31.57
Jamali	661.90	0.60	12.04	40.60	8.39	4.86	-
Kalimantan	430.10	48.45	13.70	25.99	0.18	-	45.73
Sulawesi	223.00	2.98	2.35	14.89	3.07	-	12.19
Nusa Tenggara	392.90	0.08	0.70	16.02	1.40	29.94	-
Maluku Papua	412.80	36.14	0.38	46.15	1.22	1.31	-
Total	3,261.80	95.00	57.06	154.88	23.77	60.00	89.48

We developed three scenarios of supply-side for this study: scenarios of NZE1, NZE2, and NZE3 which have different assumptions from previous studies. These three scenarios have the same electricity demand, but two of the three scenarios accommodate interconnection between regions, resulting in a different supply system among the three scenarios. This model is a novel concept, and few have applied it to prior research. The assumption for each scenario is as follows:

1. NZE1: No High Voltage Direct Current (HVDC) sea cable interconnections among regions
2. NZE2: There are HVDC sea cable interconnections which connect Jamali with Sumatra and Jamali with Kalimantan
3. NZE3: There are HVDC sea cable interconnections which connect Jamali with Sumatra, Jamali with Kalimantan, and Sumatra with Kalimantan

The power generation mix for all three scenarios during 2022 – 2030 follows the PLN RUPTL 2021 – 2030[70]. We assume that the coal-fired power plants will be phased out gradually so that in 2060 none will exist due to the absence of CCS/CCUS technology in the energy model scenario. Submarine cable transmission in scenarios NZE2 and NZE3 is predicted to be more than 80 km. The High Voltage Alternating Current (HVAC) sea cables can hardly deliver electricity at that distance or longer. The HVAC cable's insulation becomes a capacitor and absorbs the electricity[71]. So, the only possible solution is HVDC, and construction begins in 2040. It means that electricity trading among regions is not allowed before that year. The representations of NZE2 and NZE3 scenarios are shown in **Figure 5**. This concept will provide electricity stakeholders with multiple projection options for future electricity demand, electricity supply, and electricity systems.



(a)

(b)

Fig. 5: HVDC interconnections in (a) NZE2 scenario (b) NZE3 scenario among Jamali, Sumatra, and Kalimantan

3. Result and Discussion

3.1. Indonesia's electricity demand projection until 2060

Based on the projection result of electricity demand until 2060 by region, the total electricity demand for all six regions will rise from 278 TWh in 2021 to 1.910 TWh in 2060 or grow 4.9% yearly. The most significant annual growth rate is 5.7% in Sulawesi, while the lowest annual growth rate is 4.3% in Maluku Papua.

This growth leads to a change in the electricity demand share. In 2021, Sumatra, Jamali, Kalimantan, Sulawesi, Nusa Tenggara, and Maluku Papua had electricity shares of 17.1%, 67.6%, 4.8%, 6.7%, 1.9%, and 1.8% in 2021 and became 17.0%, 65.8%, 5.1%, 9.1%, 1.6%, and 1.4% in 2060 respectively (see **Figure 6**).

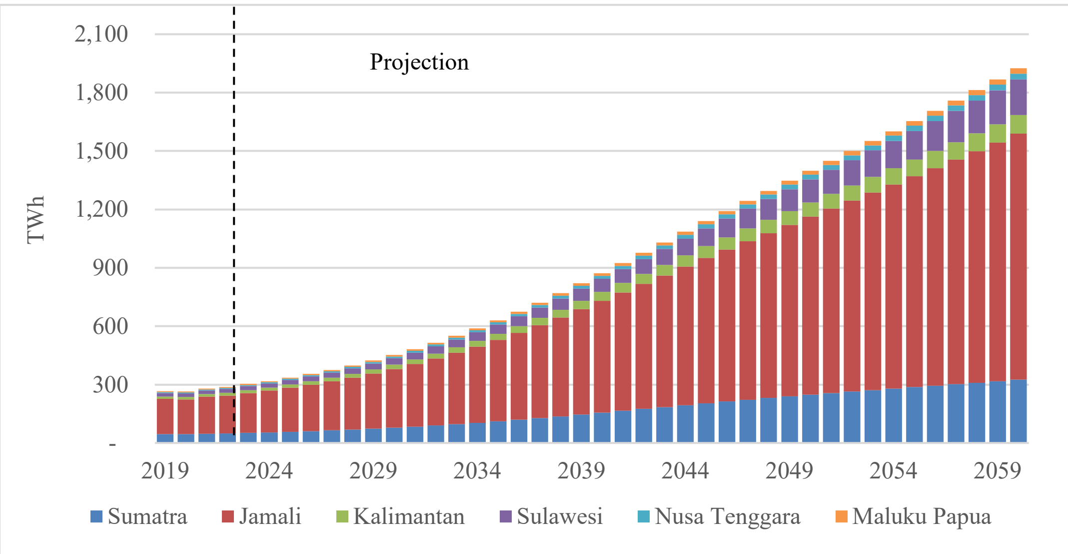
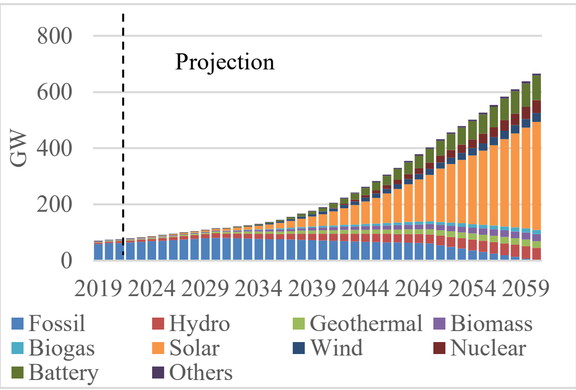


Fig. 6: Electricity demand projection

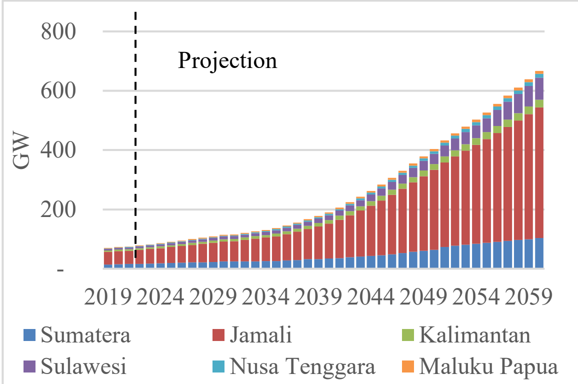
The regions that experience increasing share are Sumatra, Kalimantan, and Sulawesi. Jamali, Nusa Tenggara, and Maluku Papua are facing decreasing shares. The industrial sector in Nusa Tenggara and Maluku Papua are just a tiny part of their economic activities. Their economies are dominated by commercial sectors categorized as low energy intensive. In Sulawesi, the high electricity demand is driven by the development of high energy-intensive industries like steel and nickel. Sulawesi has several industrial parks like Sorowako, Konawe, and Morowali, which focus on smelter production.

3.2. Power generation mix based on scenario of NZE1

In the NZE1 scenario, there is no power import and export between regions due to a lack of inter-regions connectivity. Hence, if each region wants to encourage the development of renewable energy power plants, it should rely on its renewable energy resource potential (see **Table 4**). The projection of power plant capacity in this scenario gives exciting findings. All regions' overall power plant capacity will increase to 667 GW by 2060, up from 75 GW in 2021, or grow 5.7% per year. The capacity distribution of the power plants in 2060 is solar 384 GW, battery energy storage 87 GW, hydro 46 GW, nuclear 45 GW, biomass 26 GW, geothermal 24 GW, wind 32 GW, biogas 15 GW, others 8 GW (see **Figure 7a**). The capacity of battery energy storage system (BESS) will be increased significantly due to the gradual elimination of power plants that rely on fossil fuels. BESS supports intermittent power plants such as solar and wind, particularly during low or no sunlight and wind availability. To substitute fossil power plants like coal, when traditionally acting as the baseload power plants, need a tremendous amount of solar and wind because of the low-capacity factors of these RE power plants. By region, the total power plants capacity in 2060 each region: Sumatra 103 GW, Jamali 442 GW, Kalimantan 26 GW, Sulawesi 74 GW, Nusa Tenggara 13 GW, and Maluku Papua 10 GW (see **Figure 7b**). The power generation mix in Kalimantan and Maluku Papua is dominated by hydro because of the massive potential in those regions. While in other regions, solar is dominant.



(a)



(b)

Fig. 7: Power plant capacity projection (a) by type and (b) by region, the scenario of NZE1

The Jamali region exhibits a disparity between supply and demand. Jamali has an enormous need for electricity, whereas its renewable energy sources are limited (see **Table 4**). The most considerable RE resources in Jamali are just solar and wind. The RE resources such as hydro and geothermal, which can be baseload power plants to generate power for 24 hours continuously, are relatively small. So, the most feasible option for substituting fossil-fueled power plants as baseload is adopting nuclear power plants (NPPs). That's why the NPPs capacity in the scenario of NZE1 is 45 GW. All NPPs should be constructed in Jamali and fully operational for commercial purposes by 2040, with an initial capacity of 1.00 GW, as indicated in **Table 5**.

Table 5. Power plant capacity projection in Jamali (unit in GW), the scenario of NZE1

Type	2021	2030	2040	2050	2060
Fossil	40.55	51.74	44.80	37.84	-
Hydro	2.83	7.15	8.77	10.38	12.00
Geothermal	1.25	3.05	6.20	8.20	8.40
Biomass	0.22	0.22	3.49	6.74	10.00
Biogas	0.002	0.01	0.67	1.34	2.00
Solar	0.06	3.86	36.13	132.64	279.71
Wind	0.001	0.26	5.17	10.09	15.00
Nuclear	-	-	1.00	22.50	45.00
Battery	-	0.80	10.00	37.50	65.00
Others	0.03	0.49	1.40	2.91	3.46
Total	44.94	67.58	117.63	270.15	440.57

3.3. Power generation mix based on scenario of NZE2

In the scenario of NZE2, there are two inter-region connections: the Jamali grid with the Sumatra grid and the Jamali grid with the Kalimantan grid through an HVDC sea cable. We set these interconnections to start in 2040 based on the results of a scenario of the NZE1, showing that the NPPs started to supply electricity that year. Therefore, we would like to see if there is an impact on the NPP capacity in the NZE2 scenario if the electricity trading starts in 2040.

The establishment of these interconnections resulting different outcomes in comparison to scenario NZE1. The overall power plant installed capacity in 2060 is higher than the scenario of NZE1 without interconnections. The total capacity in 2060 of the NZE2 is 690 GW cause of the import of electricity from Sumatra and Kalimantan to Jamali. The electricity imported from Sumatra and Kalimantan to Jamali comes from RE power plants with lower capacity than NPPs. As a result, the installed capacity of power plants in Jamali is lower, while the power plant capacity in Kalimantan and Sumatra is higher than in scenario NZE1 (see **Table 6**).

Table 6. (a) Total power plant capacity projection in 2060 (unit in GW) for all regions, (b) Total power plant capacity projection in 2060 (unit in GW) per region.

(a)

Type	NZE1	NZE2	NZE3
Fossil	-	-	-
Hydro	46	64	68
Geothermal	24	24	24
Biomass	26	30	30
Biogas	15	17	17
Solar	385	390	362
Wind	32	44	43
Nuclear	45	25	25
Battery	87	87	86
Others	7	10	10
Total	667	690	664

(b)

Region	NZE1	NZE2	NZE3
Sumatra	103	125	93
Jamali	441	408	408
Kalimantan	26	59	64
Sulawesi	75	75	75
Nusa Tenggara	13	13	13
Maluku Papua	10	10	10
Total	667	690	664

The total NPPs capacity to be built in Jamali based on the scenario NZE2 is smaller than in scenario NZE1, at 25 GW in 2060, compared to 45 GW in scenario NZE1. The first NPPs are not necessarily to be built in 2040, but they can be delayed until 2045 with starting installed capacity of 1.5 GW. The electricity import from Sumatra and Kalimantan to Jamali will commence in 2040 and gradually increase to 145.4 TWh in 2060. The electricity import is given in **Table 7**.

Table 7. Electricity Trading (unit in TWh), the scenario of NZE2

Export	2040	2045	2050	2055	2060
Sumatra to Jamali	1.21	9.37	20.76	34.80	43.78
Kalimantan to Jamali	2.42	18.74	41.52	69.59	101.62
Total	3.63	28.11	62.28	104.39	145.40

3.4. Power generation mix based on scenario of NZE3

In the scenario of NZE3, there is an expansion of the interconnection system. Three HVDC sea cable interconnections connect the regions of Jamali with Sumatra, Jamali with Kalimantan, and Sumatra with Kalimantan. Kalimantan has considerable hydro resources which have a higher capacity factor than intermittent/variable renewable energy like solar and wind. Hydropower plants can generate electricity at a low cost compared to other power plants type, even fossil-fueled power plants.

The total installed capacity of the NZE3 scenario in 2060 is 664 GW, lower than the NZE1 cause of electricity import from Kalimantan to Sumatra. Due to this import, the RE power plants' generating capacity in Sumatra can be lowered, particularly solar. Solar power plants in Sumatra can be replaced byhydropower plants in Kalimantan which are less expensive and have a higher capacity factor. As a result, the total installed capacity in Kalimantan is higher than NZE1 and NZE2, mostly from hydro. The installed NPPs capacity in the scenario of NZE3 is the same as the NPPs capacity in NZE2, in which first NPP connect in 2045 and all NPPs are still in Jamali (see **Table 6a**).

In the NZE3 scenario, power trading occurs between Sumatra-Kalimantan, Sumatra-Jamali, and Kalimantan-Jamali. Sumatra will import up to 18.4 TWh of power from Kalimantan from 2040 to 2060 (see **Table 8**). The total electricity trading in NZE3 is slightly higher than in the NZE2 scenario.

Table 8. Electricity Trading (unit in TWh), the scenario of NZE3

Export	2040	2045	2050	2055	2060
Sumatra to Jamali	0.79	9.37	20.76	34.80	31.43
Kalimantan to Jamali	2.42	18.60	40.98	68.26	100.07
Kalimantan to Sumatra	0.42	3.40	7.74	13.17	18.39
Total	3.63	31.37	69.48	116.23	149.89

Across all scenarios, The NPP capacity differs from the findings of numerous prior research. The distinctions are outlined in **Table 9** below.

Table 9. NPPs capacity based on prior research.

Research	NPPs Capacity	First Operating Year
MEMR's net-zero emissions roadmaps[72]	31 GW in 2060	Started at 2039 Connected to the system in 2049
Kamia Handayani et.al (Renewable energy scenario)[50]	22 GW in 2050	First installed in 2035
Satria Putra Kanugrahan (Advanve Scenario)[55]	15,69 GW in 2060	-
IEA (Announced Pledges Scenarios)[19]	8 GW in 2060	Effective in 2040

Based on the current interconnection between Jawa and Bali, the concept of an HVDC sea cable that connects three regions, Jamali, Sumatra, and Kalimantan, will provide greater reliability in electricity transmission if one of the HVDC sea cable transmissions experiences a problem. All or some NPPs can be constructed outside Jamali, but the consequences are apparent, to meet Jamali's demand for electricity, the capacity of electricity trading among regions will increase as high as the capacity of NPPs that will be moved outside Jamali.

Most of the NPP's raw material reserves are located outside Jamali, so constructing nuclear power plants outside Java is considered more profitable because it will reduce transportation costs. In addition, Bangka (Sumatra), and West Kalimantan, where feasibility studies have been conducted, are considered safer from a disaster perspective than the Jamali region[32]. Based on data from BATAN, Indonesia has Uranium reserves in yellow cake (U_3O_8) of around 90 thousand tons and Thorium of 140 thousand tons. The distribution is in the Kalimantan region: 45.7 thousand tons of Uranium, 7 thousand tons of Thorium, and the Sumatra region: 43.7 thousand tons of Uranium, 135.2 thousand tons of Thorium[73,74].

Referring to Imam Bastori's research results, 1 NPP of the PWR type with a capacity of 1 GW requires 244.68 tons of yellow cake[75]. Following the NPP capacity of the NZE1 scenario, the need for yellow cake reaches 118,1 thousand tons from 2040 to 2060, and Indonesia's reserves will be exhausted in 2058. After that year, Indonesia must import uranium to meet the raw material demand. Compared to NZE2 and NZE3, with a nuclear power plant capacity of 25 GW in 2060, U_3O_8 reserves will run out in a more extended period of 2066, noting that NPP capacity will not increase after 2060.

Building interconnections among regions does not significantly impact GHG emission from the power sector because of little change in the fossil-fueled power plant projection. The GHG emission will rise to about 367 million tons of CO_2 eq. in 2032 from 280 million tons of CO_2 in 2021. After peaking in 2032, the emissions will drop to zero in 2060. The pathway of GHG emissions for the NZE scenarios is shown in **Figure 8**.

The power capacity projection from 2022 to 2030 uses PLN RUPTL 2021 – 2030 causing the GHG emission to rise until 2032. As we know, fossil-fueled power plants still dominate the PLN RUPTL projection during that period.[70]

The total system cost of each scenario is defined as the total cumulative discounted cost of electricity production in all regions. In this study, we use a discount rate of 10%. The assumed cost of constructing an HVDC submarine cable transmission is USD 2.5 million/km for a power capacity of 2,500 MW with a voltage of +/- 500 kV[76]. The assumption of the length of submarine cable transmission between Jamali and Sumatra is 50 km, between Jamali and Kalimantan is 600 km, and between Sumatra and Kalimantan is 600 km. From the model results, the total system cost of the NZE1, NZE2, and NZE3 scenarios are 266, 262, and 261 billion US$, respectively. These total discounted costs exclude the GHG emission cost.

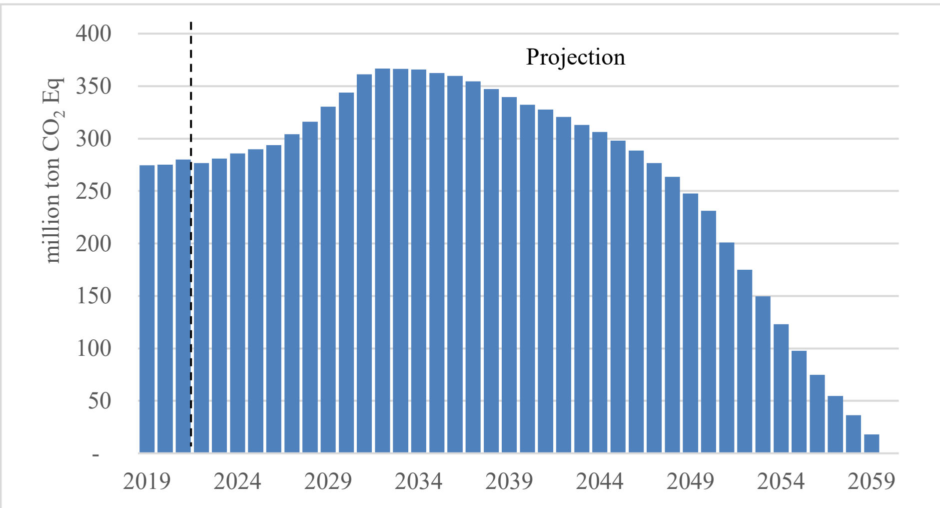


Fig. 8: GHG emissions of NZE scenario

4. Conclusion

The construction of nuclear power plants in Indonesia is a topic that elicits controversy characterized by ambiguity and uncertainty of nuclear policy. This situation will soon change, as Indonesia has committed to implementing green energy transition pathways that will result in zero net emissions by 2060. The results of this study indicate that there will be a mismatch between energy supply and demand if we rely on new and renewable energy sources. Jamali has a high electricity demand but few potential renewable energy resources. However, other regions such as Sumatra, Kalimantan, Sulawesi, and Papua exhibit relatively low electricity consumption levels but possess tremendous untapped potential for renewable energy sources.

We modelled grid interconnections among regions, and the findings are surprising. In all scenarios, the model states there will be NPPs in the power generation mix by 2060. The absence of grid interconnections among regions in the scenario of NZE1 resulted in a huge installed capacity of nuclear power plants in 2060 (45 GW), which is higher than in the NZE2 and NZE3 scenarios (25 GW each). The grid interconnections among regions will reduce the NPP's installed capacity by about half, and the commercial operation date of the NPPs can be delayed to 2045, starting with 1,56 GW. The role of NPPs in the power generation mix is as an option to replace fossil-fueled power plants as a baseload in the absence of CCS/CCUS technologies to support carbon-neutral targets in Indonesia. The option of the NZE3 scenario gives the best total discounted cost, which means that building an interconnection grid among Jamali, Sumatra, and Kalimantan islands would give the best option toward Net Zero Emissions and NPPs contribution of 3,77% in the power generation mix in 2060. All or several NPPs could be constructed outside Jamali region.

Different assumptions or input settings could result in distinct outcomes. The energy model simulation based on aggregate data may not accurately capture the specifics of a location. Additionally, this paradigm calls for increased stakeholder participation, input, and involvement. Participation of various stakeholders, such as local communities, business leaders, and policymakers, can validate data on area requirements, aspirations, and restrictions more thoroughly, improving the accuracy of the underlying assumptions. This research needs to enhance modeling techniques, detail the data analyzed, and validate the underlying assumptions used to increase the research's credibility.

This study's findings can inform long-term energy planning strategies in Indonesia by energy policymakers, planners, and energy-related commercial players, such as PLN. This model can assist in determining the best combination of power generation technologies to meet energy demand in a region, including local renewable energy, by considering multiple factors such as cost, environmental impact, and energy security. To identify and assess potential future business possibilities, business players and investors in the energy sector must know the predicted future demand. On the policymaker side, the findings of this study can serve as a basis for creating NPPs regulations that will clarify previously ambiguous. This study's findings can guide researchers to establish priorities for advancing energy technology following the demand for and potential of current renewable energy sources. NPP research and development must continue to create a safer, more effective, and less expensive system.

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