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Review/Research Article

Sustainable Long-Term Energy Supply and Demand: The Gradual Transition to a New and Renewable Energy System in Indonesia by 2050

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Abstract. The objective of this work is to evaluate long-term energy demand and supply decarbonization in Indonesia. On the demand side, electric vehicles and biofuels for transportation and induction stoves and urban gas networks for households were considered. Based on the National Energy Policy, primary energy supply projections optimized NRE power plant use and increase NRE's position in the national energy mix. A Low Emissions Analysis Platform (LEAP) model evaluates 2020–2050 energy demand predictions and low-carbon energy systems. This study's sustainable transition options require two basic technical advances. First, electric vehicles and induction stoves would reduce oil fuel usage by 228.34 million BOE and LPG consumption by 24.65 million BOE. Second, power generation should be decarbonized using NRE sources such as solar, hydro, biomass, geothermal, and nuclear. In 2050, solar power (40 GW), hydropower (38.47 GW), geothermal power (10 GW), and other NRE (24.45 GW, 18.67 GW of which would be biomass power) would dominate NRE electrical capacity. Biomass co-firing for coal power plants would reach 36.35 million tons in 2050. In 2035, the Java-Bali or West Kalimantan system will deploy 1 GW of nuclear power reactors, rising to 4 GW by 2050. Under the Transition Energy (TE) scenario, by 2025 and 2050, new and renewable energy would make up 23% and 31% of the primary energy mix, respectively, reducing GHG emissions per capita. According to predictions, annual GHG emissions per capita will decline from the BAU scenario's 4.48 tonne CO2eq/capita in 2050 to the TE scenario's 4.1 tonne.

Keywords: Sustainability; Decarbonization; NRE; GHG emissions; LEAP.

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1. Introduction

Sustainability is made up of three different parts: protecting the environment, keeping the economy going, and helping people (Oyedepo, 2012). Energy is connected to these three things in a roundabout way. Almost every part of the economy, such as industry, transportation, household, commercial, and other sectors, depends on energy resources. From the energy supply side, both fossil fuels and renewable energy come from the environment, and most of the waste from energy processes (making, moving, storing, and using energy) goes into the environment (Oyedepo, 2012). Energy sustainability provides an opportunity to change society and grow the economy. It is also necessary to meet the growing demand for energy and reduce the world's carbon footprint (Khan *et al.*, 2022).

The five primary objectives of a sustainable energy perspective are reduced carbon dioxide emissions, no detrimental ecological impacts, increased energy transformation reliability, lower costs of energy production, and enormous adoption of renewable energy technology (Vidadili *et al.*, 2017);(Adewuyi *et al.*, 2020). These goals for energy sustainability are called the "energy trilemma": making energy affordable and easy to get, making sure energy is secure, and making sure it doesn't hurt the environment. This will create a solid foundation for economic growth and competitiveness (Khan *et al.*, 2022).

The field known as "energy security and transition" addresses problems pertaining to the accessibility of energy as well as the proportion of sources of clean energy in the total energy supply (Dialga, 2021). The advancement of sustainable energies has a major influence on the entire nation, including the generation of energy from domestic sources, new local employment opportunities, and an increase in knowledge and level of expertise in specific green energy technologies. This is in addition to achieving independence, energy security, and reducing greenhouse gas emissions (Dialga, 2021).

Further, the purpose of energy transition mechanisms is to reduce global warming by eliminating fossil fuels, especially coal in the near future, decarbonizing electricity generation, and electrifying end-use sectors as essential steps toward decarbonizing the entire energy system (Vidinopoulos *et al.*, 2020). Thus, it is necessary to switch toward greener forms of energy generation, like renewables. The transition to renewable energy sources will be time-consuming, but it will have far-reaching benefits for the planet and its inhabitants (Lin *et al.*, 2022).

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The Government of Indonesia's Policy Regulation for Energy Development at the National Level (KEN, No. 79/2014) lays out the directions and actions needed to speed up the energy transition by promoting new and renewable energy (NRE). By 2025, NRE will make up at least 23% of the primary energy mix, and by 2050, it will make up at least 31% of the primary energy mix (GoI, 2014). KEN has been converted into Law No. 22/2017 of the President on the Planning Scheme of National Energy in order to make it operational (GoI, 2017).

Without non-commercial biomass, the overall sum of primary energy produced in 2020 is 1,440.2 million BOE. This is made up of 38.5% coal, 32.8% oil, 17.4% natural gas, and 11.2% NRE. The goal set by the General Plan of National Energy (RUEN), which is 14%(GoI, 2017), has not been met for the NRE share. In addition, primary energy rose at a moderate annual rate of 2.97 percent from 2010 to 2020 (KESDM, 2021). This fundamental energy is utilized to generate final energies such as electricity and fuel oil (refinery products).

The national installed capacity and electricity production in 2020, including both on-grid and off-grid systems, are 72.81 GW and 299.96 TWh, respectively (KESDM, 2021). The coal-fired power plants accounted for 47.53% (34.61 GW), followed by gas-fired power plants (29.53%, 21.72 GW), oil-fired power plants (8.20%, 5.97 GW), and the remainder are renewable energy-based power plants (14.4 percent, 10.52 GW) (KESDM, 2021), which is less than the General Plan of National Energy (RUEN) objective of 16.2 GW(GoI, 2017). It is evident that Indonesia continues to rely largely on coal-fired power facilities. Coal produces the highest greenhouse emissions and the least energy per thousand tons. It's the cheapest fuel, but renewables are growing (Rahman *et al.*, 2021).

Hydropower (8.4%, 6.14 GW), geothermal power (2.9%, 2.13 GW), biomass power (2.4%, 1.78 GW), solar power (0.3%, 0.185 GW), wind power (0.2%, 0.154 GW), and other renewables (0.2%, 0.124 GW) make up the 14.45% of power plants that use renewable energy (KESDM, 2021). Hydropower and geothermal power make up most of the installed renewable energy capacity, while most of the other renewable energy sources are not very well developed. In 2020, biomass, solar, and wind made up less than 3% of the installed capacity, with off-grid applications making up the majority (Sani *et al.*, 2021). Even though new policies were made to speed up the development of solar power, only 49 MW and 39.5 MW of capacity were added in 2019 and 2020, respectively. The first wind farm in Indonesia opened in July 2018, and another one opened in 2019. Together, they have a total installed capacity of 154.3 MW (Sani *et al.*, 2021).

Indonesia relies heavily on oil, coal, natural gas, LPG, and electricity for its final energy needs. In the years between 2010 and 2020, total energy consumption increased at a pace of 2.4% (excluding non-commercial biomass) (KESDM, 2021). The final energy consumption of the transportation and household sectors has a substantial impact on energy subsidies.

The transportation sector uses a lot of oil-based fuels, so it's a big part of Indonesia's energy mix. However, Indonesia has been a net oil importer since 2004. Over 60% of the oil that Indonesia uses goes to this sector, and 70% of that goes to road transportation. The Indonesian government's subsidization of gasoline and diesel fuels is a major issue for road transportation energy. If the policy doesn't change, rising demand for those fuels will lead to more subsidies, which will worsen as domestic oil supply declines (Deendarlianto et al., 2017). So, it's important to look into other options, like electric vehicles (EVs) and biofuel, for bringing in new types of energy or fuel for road transportation.

Indonesia's Presidential Regulation 55/2019 promotes EVs adoption (GoI, 2019). The EVs regulation is an umbrella for future derivative legislation. Norway, Iceland, Sweden, and the Netherlands have above 5% EV penetration. EV market share exceeds 20% in some Chinese and US cities. Indonesia could apply lessons learned and best practices to its circumstances (Adiatma & Marciano, 2020).

Meanwhile, the residential LPG subsidy puts a strain on Indonesia's budget. According to the 2019 State Budget of Indonesia, the LPG subsidy for 3 kg cylinders will cost more than $4.9 billion in 2019. Indonesia, on the other hand, is building many new power plants with up to 35,000 MW of capacity (megawatt). Due to the slowdown in economic growth, the added capacity will cause power overcapacity. Thus, Indonesia's induction stove program converts households to electric cooking to use excess power and reduce LPG subsidies (Hakam *et al.*, 2022).

Induction cooker use is encouraged in several nations. Ecuador's national initiative replaced three million gas burners with induction stoves. Energy imports account for 80% of Ecuador's residential gas use. Ecuador's LPG-to-induction stove program failed for many reasons. Due to high start-up costs and the incorrect belief that induction stoves raise electricity bills, the 2018 target of 3.5 million homes adopting induction stoves was not attained (Gould *et al.*, 2020). Moreover, in Himachal Pradesh, one of India's most electrified states, over 4000 rural households received induction stoves for clean cooking. Electricity mostly displaced LPG, a supplementary cooking fuel, but not mud stoves. 5% of households switched to electric cooking (Banerjee *et al.*, 2016).

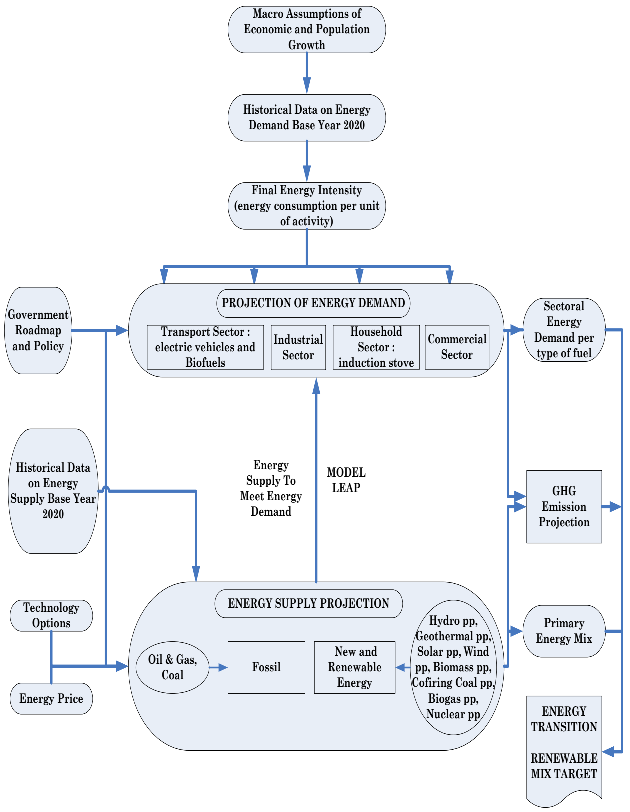
This paper aims to analyze sustainable transition strategies by decarbonizing long-term energy demand and supply in Indonesia. On the demand side, by taking into account the program of electric vehicles and biofuels for the transportation sector and induction stoves and urban gas networks for the household sector, with the base year 2020, this energy demand will be projected per type (fuel, electricity, gas, LPG, coal, biofuel, biomass). On the supply side, projections of primary energy supply (fossils and NRE) will be carried out by optimizing the use of NRE plants and increasing the share of NRE in the national energy mix based on the provisions of the National Energy Policy. The resulting CO_2 emissions over the study's time horizon were also investigated. The analysis is carried out with the help of a Low Emissions Analysis Platform (LEAP), and the emission factors are based on IPCC Tier 1, which is already outfitted with LEAP software (Indrawan *et al.*, 2017).

2. Materials and Methods

2.1 Research Framework

The study Sustainable Long-Term Energy Supply and Demand: Indonesia's Gradual Transition to a New and Renewable Energy System by 2050 requires an analytical framework, as shown in Figure 1. So the study's goals can be realized. The evaluation of the final energy demand projection and the primary energy supply projection make up the analysis framework. Economic growth grow (Edi Hilmawan *et al.*, n.d.), population expansion (BPS RI, 2018), policy, and a roadmap for energy development are used to calculate predicted energy demand.

The use of different energy sources and the potential of energy resources, as well as the rules that are already in place and the progress of energy technology, are also taken into account in the analysis of the primary energy supply (National Energy Council, 2019).



Sources : (Edi Hilmawan *et al.*, n.d.),(National Energy Council, 2019)
Fig. 1 Framework analysis on sustainable long-term energy supply and demand

This study must consider roadmaps and government policies regarding the demand and supply of each type of energy, such as the energy transition roadmap towards carbon neutrality (Ministry Of Energy And Mineral Resources, 2021), the business model for electricity provision (PT.PLN (Persero), 2021), the legally required biofuel development program mandated by MEMR regulation No. 12/2015 (KESDM, 2015), the development of vehicles powered solely by electricity in Indonesia based on the quantitative target for the development of the national motor vehicle industry from the Ministry of Industry (Direktur Jenderal Industri Logam, Mesin, Alat Transportasi, Dan Elektronika, 2021), and the mega conversion from LPG to induction stove (Ministry Of Energy And Mineral Resources, 2021);(Hakam *et al.*, 2022).

For figuring out how certain technologies affect energy demand and supply, both new and renewable energy (NRE) technologies for the electrical sector and new and improved end-use technologies that need less energy are taken into account. To meet the target for the renewables mix, solar power, geothermal power, hydropower, pumped hydro storage, biomass power, biomass co-firing at coal-fired power plants, and nuclear power are all being studied. (PT.PLN (Persero), 2021).

For this research, the energy sector in Indonesia is modeled with an application software called LEAP (Low Emissions Analysis Platform), and the Next Energy Modeling System for Optimization (NEMO), which is tightly integrated with LEAP, was used to calculate the least-cost optimization (Heaps, 2021); (Charles Heaps, Eric Kemp-Benedict, 2021);(Ordonez *et al.*, 2022).

Here are some of the LEAP studies undertaken in the Asia area. Sani *et al.* (Sani *et al.*, 2021) compared the role of modern renewables in the Sumatran power sector to the Indonesian government's plans. Ordonez *et al.* (Ordonez *et al.*, 2022) examined cost-optimized methods for integrating greater proportions of renewable energy into the Indonesian power grid. Handayani *et al.* (Handayani *et al.*, 2019) studied long-term renewable energy scenarios with technological learning in mind for the Java-Bali electrical system development in Indonesia. Kachoee *et al.* (Kachoee *et al.*, 2018) assessed the effects of various energy policies on electricity demand and supply, the possibility of lowering greenhouse gas emissions, and the cost to Iranian society. Using renewable energy resources, Kumar and Madlener (Kumar & Madlener, 2016) examined India's future sustainable electricity supply. Considering the baseline scenario, renewable sources, optimum clean coal, and energy efficiency and conservation cases, (Mirjat *et al.*, 2018);(Tanoto *et al.*, 2021) used LEAP to evaluate 2050 Pakistan's long-term electricity distribution side cases.

2.2 Scenario

A scenario is a set of assumptions used to run the model, whose implications are assessed for the entire energy system. This paper compared the "business as usual" (BAU) scenario to the "energy transition" (TE) scenario. For both scenarios, the GDP growth was assumed to be the same.

The BAU scenario refers to the current state and predictions up to 2050 based on data from the past several years, such as additional city gas, electric stoves, electric automobiles, and others. Additionally, the Business Plan for Electricity Provision (RUPTL 2021–2030) guides power plant development.

The TE scenario refers to the adoption of electric vehicles (EVs), induction cooktops, and urban gas networks (jargas) in accordance with the roadmaps developed by the Ministry of Industry for the development of electric vehicles (Direktur Jenderal Industri Logam, Mesin, Alat Transportasi, Dan Elektronika, 2021) and the Ministry of Energy and Mineral Resources for the energy transition roadmap toward carbon neutrality (Ministry Of Energy And Mineral Resources, 2021). When deciding how much the energy system needs to grow, the NRE goal of the National Energy Policy for 2014 (KEN 2014) is taken into account(GoI, 2014). In both scenarios, a nuclear power plant is anticipated to be in operation by 2035. Under the BAU and TE scenarios, nuclear PP capacity in 2050 would be 1 GW and 4 GW, respectively.

2.3 Macro Assumptions

The following are some of the key assumptions that were used as input for the model: population growth (BPS RI, 2018), gross domestic product (GDP) (Edi Hilmawan *et al.*, n.d.), sales of EVs under the BAU scenario (Edi Hilmawan *et al.*, n.d.),(PT.PLN (Persero), 2021) and TE scenario (Kementerian Perindustrian, 2020), sales of induction stoves, and the development of gas networks in urban areas (jargas) (Ministry Of Energy And Mineral Resources, 2021) for household demand. These assumptions are outlined in Tables 1 and 2, respectively.

Table 1
Assumptions on GDP and population growth

Macro Assumptions	Year 2020	2025	2030	2040	2050
Population (million)	270.2	283.1	294.8	313.3	324.6
Population Growth (%/year)	1.16	0.94	0.81	0.54	0.3
GDP Growth (%/year)	-2.07	5.17	5.5	5.5	4.5

Source : (Yudiartono *et al.*, 2022)

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Table 2
Programs considered in each scenario

Programs	Scenario	Year			
		2020	2025	2040	2050
Electric Car Sales (thsnd)	BAU	0.26	42.28	420	885
	TE	0.26	400	1500	2800
Electric motorcycle sales (thsnd)	BAU	2.01	311	1944	3042
	TE	2.01	1760	4375	7875
Induction stove (mill. household)	BAU	0	0.3	1.2	2.2
	TE	0	8.2	38.2	48.2
Jargas (mill. household)	BAU	0.267	2.5	6.7	10.3
	TE	0.267	5.2	20.3	23.4

Note: Jargas is an urban gas network
Source: (Yudiartono *et al.*, 2022)

All scenarios assume the same population growth and economic growth rates between 2020 and 2050. In the BAU scenario, the number of electric vehicles (EVs) will reach approximately 42.3 thousand for electric cars and 311 thousand for electric motor cycles in 2025, according to Outlook Energy Indonesia 2021 and RUPTL's program. In the TE scenario, on the other hand, the domestic automotive industry is expected to produce 400 thousand electric cars and 1,760 thousand motorcycles by 2025, according to a goal set by the Ministry of Industry for the development of electric vehicles (see Table 2). The Ministry of Industry's electric vehicle production goal only extends to 2035. Consequently, the number of EVs manufactured between 2036 and 2050 is based on the prior growth history of electric vehicles.

Indonesia's induction stove initiative converts homes to electric cooking to utilize excess power and lower LPG subsidies. The scheme will replace LPG stoves in 8.2 million households by 2025 and 48.2 million by 2050 with induction stoves (Ministry Of Energy And Mineral Resources, 2021).

3. Empirical Results and Discussions

3.1 Final Energy Demand Projection

Because of ongoing economic and demographic factors, energy demand is predicted to keep going up. In the time frame under consideration, both the economy and the population would expand at an annualized rate of 5.03% and 0.633%, respectively. Table 3 indicates that overall final energy demand (excluding non-commercial biomass) would ascend from 845.26 million BOE in 2020 to 2,846.19 million BOE and 2,593.20 million BOE in 2050 under the BAU and TE scenarios.

The variations in fossil fuel consumption by fuel type from 2020 to 2050 are presented in Table 3. In the BAU scenario, oil fuels and LPG consumption climbed from 222.79 million BOE and 69.72 million BOE, respectively, to 659.93 million BOE and 115.78 million BOE. In 2050, oil fuels and LPG consumption under the TE scenario are expected to be 340.37 million BOE and 29.5 million BOE, respectively, a reduction of 319.56 million BOE and 86.28 million BOE as compared with the BAU scenario. These decreases would be substituted by an increase in electricity consumption; by 2050, its consumption would reach 809.03 million BOE (1,337.14 TWh) under the TE scenario compared to 674.46 million BOE (1,114.73 TWh) for the BAU scenario. Such an increase is a consequence of electric vehicle deployment in the transportation sector and the planned switchover from liquefied petroleum gas to induction stoves in the household sector.

Table 3
Projection of final energy demand by type (million BOE)

Energy Type	Scenario	Year		
		2020	2025	2050
Electricity	BAU	162.16	206.33	674.46
	TE	162.16	221.54	809.03
Oil Fuels	BAU	222.79	270.31	659.93
	TE	222.79	241.29	340.37
Gas	BAU	97.48	110.32	345.87
	TE	97.48	113.44	364.15
Coal	BAU	113.60	125.45	381.47
	TE	113.60	125.45	381.47
LPG	BAU	69.72	82.02	115.78
	TE	69.72	69.29	29.50
Biofuel	BAU	179.32	222.3	667.65
	TE	179.32	222.3	667.65
Biogas	BAU	0.18	0.39	1.03
	TE	0.18	0.39	1.03
Total	BAU	845.26	1017.11	2846.19
	TE	845.26	993.69	2593.20

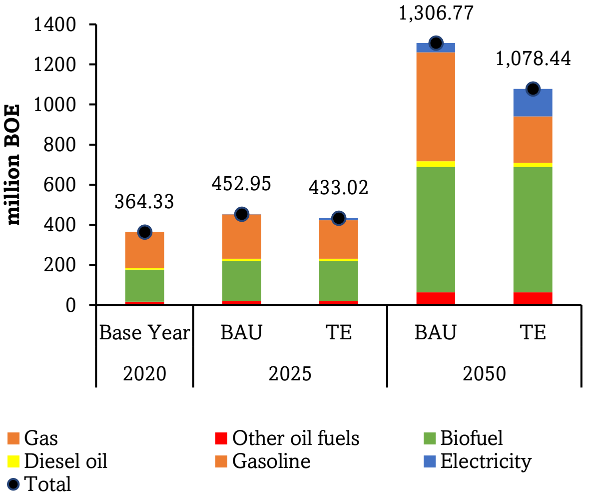
On the other hand, coal is used in manufacturing (cement, paper, textiles, etc.) and base-load power generation. Its use is growing at an average rate of 4.1% per year, but it is still used much less than electricity. In the last 10 years, the government has made CPO-based biofuels, which are mixed with diesel fuel to make B30 (30% biodiesel and 70% diesel). Biodiesel is a renewable alternative to diesel fuel with lower CO2 emissions because it is carbon neutral. This is good for the environment and long-term growth (Deendarlianto *et al.*, 2020). Under the BAU and TE scenarios, it is expected that the final energy demand for biofuel would go from 179.32 million BOE in 2020 to 667.65 million BOE in 2050, which is almost 4 times what it was in 2020.

There are many different applications for biofuels, including in transport, industries, commerce, and even power plants. Lack of access to sufficient raw materials prevents widespread usage of bioethanol.

3.1.1 The Effect of The Electric Vehicle on Energy Demand

The transportation sector comprises road, rail, air, and water modes, which utilize the final energy of oil fuels. Gas, or CNG, is only used for road transportation, and electricity is for electric rail transportation and electric vehicles. Electric vehicles under the BAU scenario refer to current conditions, where the sales percentage of electric vehicles in the future will not be as great as it is in the TE scenario. The 2020 Ministry of Industry Regulation No. 27 outlines a strategy for the development of electric vehicles. This is the subject of the TE scenario.

Figure 3 demonstrates that the mass-scale deployment of electric vehicles in the TE scenario can reduce the overall final energy demand during the whole study period. In 2050, overall energy usage is projected to be 1,306.77 million BOE under the BAU scenario, compared to 1,078.44 million BOE under the TE scenario, a decrease of 228.34 million BOE. This is because the percentage of electric vehicle sales in the BAU scenario is only 29.5%, much lower than the TE scenario, which reaches more than 90%. Besides that, electric vehicles use less energy than cars that run on gasoline (internal combustion engines). More than 77% of the grid's electricity is transformed into mechanical energy by the motors of EVs (US Department of Energy 2020).



Note: Other oil fuels include avtur, avgas, fuel oil, and kerosene

Fig. 3 Projection of final energy demand by type for the transportation sector

Most gasoline-powered cars turn between 12 and 30% of the energy in the gasoline into power at the wheels. Electric vehicles, on the other hand, could be three times more energy efficient than cars with internal combustion engines (US Department of Energy 2020).

As shown in Figure 3, the higher ownership rates of electric vehicles under the TE scenario than in the BAU scenario, would boost the transportation sector's electricity demand. The demand for electricity would increase from 10.54 million BOE (17.42 TWh) in 2025 to 137.36 million BOE (227.02 TWh) in 2050 at a pace of about 11% annually.

Meanwhile, according to the General Plan of National Energy (RUEN), the transportation sector will use 2.3 TWh and 31.6 TWh of electricity in 2025 and 2050, respectively. This is accomplished with a 2025 goal of 2,200 units of four-wheeled electric vehicles, which is far lower than the government's goal of 400,000 units. Unfortunately, the 2050 goal for RUEN electric vehicles is not specified.

Optimizing the electrification of road transportation also reduces gasoline and diesel oil consumption: in the TE scenario, gasoline and diesel oil consumption in 2050 are 232.77 million BOE and 19.71 million BOE, respectively, compared to 544.09 million BOE and 27.95 million BOE in the BAU scenario. The fall in the transportation sector's demand for gasoline and diesel oil would significantly reduce its reliance on imported fossil fuels. As a result, the greatest impact on oil consumption is from the adoption of innovative energy-efficient devices, such as electric vehicles in the transportation sector.

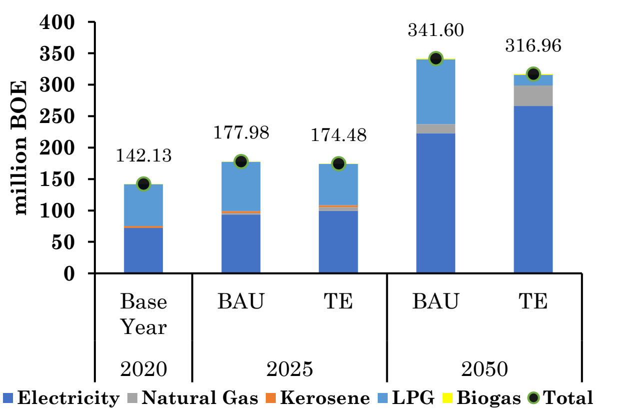


Fig. 4 Projection of final energy demand by type for the household sector (excluding non-commercial biomass)

3.1.2 The Effect of Migration Program for LPG to Induction Stoves and City Gas Networks on Energy Demand

Under the TE scenario, household energy demand (excluding non-commercial biomass) is predicted to increase from 142.13 million BOE in the base year to 316.96 million BOE in 2050, a drop of 24.65 million BOE from the BAU scenario. This is because induction stoves are more efficient (81.78%) than LPG stoves (45.06%) (Hakam *et al.*, 2022).

The LPG to electricity conversion program would change Indonesian households' fuel composition in cooking activities. Figure 4 depicts how, in 2050, LPG consumption would fall from 103.26 million BOE (30.23%) in the BAU scenario to 16.98 million BOE (5.36%) in the TE scenario. These decreases would be offset by increased electricity consumption, from 222.85 million BOE (65.24%) to 266.2 million BOE (83.99%) under BAU and TE scenarios, respectively. The demand for natural gas also continues to increase; by 2050, its consumption will reach 14.47 million BOE (4.23%) under the BAU scenario. Due to the development of gas pipeline networks in urban areas, the consumption of such natural gas would rise considerably to 32.75 million BOE (10.33%) in the case of the TE scenario.

3.2 Projection of Primary Energy Supply

Indonesia's principal energy sources include crude oil, coal, natural gas, and new and renewable energies (hydropower, geothermal, solar, wind, biomass, bioenergy, and nuclear). In industry, coal is also used as a final source of energy, and natural gas is used as a final source of energy in industry, residential, and commercial sectors (Minister for Environment and Forestry, 2021).

The primary energy supply is projected to increase by 4.0% per year under the BAU scenario and 4.2% per year under the TE scenario between 2020 and 2050. Figure 5 displays the forecasted distributions of primary energy sources. In both cases, coal is the primary fossil fuel used to power utilities. As a result of the transportation industry, oil's importance remains high. As more people switch to electric vehicles, demand for primary energy sources, particularly coal in the TE scenario, will rise.

3.3 Comparison of Primary Energy Mix Between BAU Scenario and TE Scenario

In 2020, under the BAU scenario, the NRE mix only accounted for 11.2% of total primary energy supply. By 2025, the share of NRE is estimated to be only 18.13%, and by 2050, it will be 20.79%, which is still quite far from the target of National Energy Policy Regulation 79/2014 (KEN).

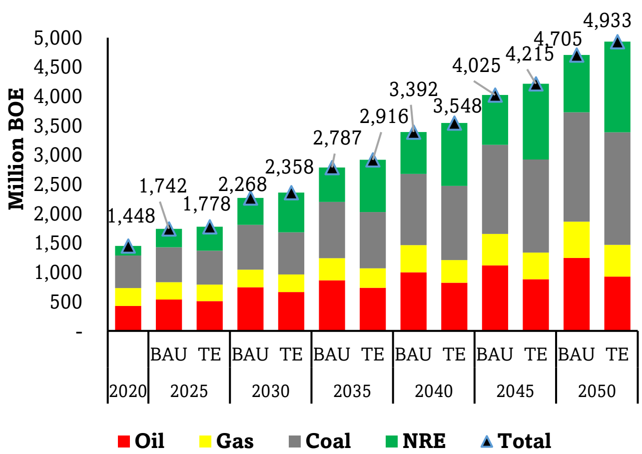


Fig. 5 Projection of primary energy supply

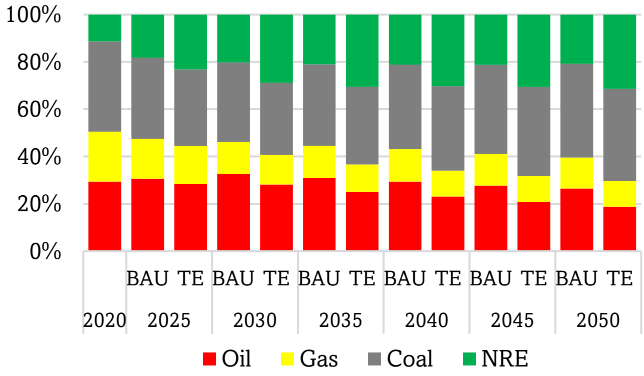


Fig. 6 Primary energy mix projection

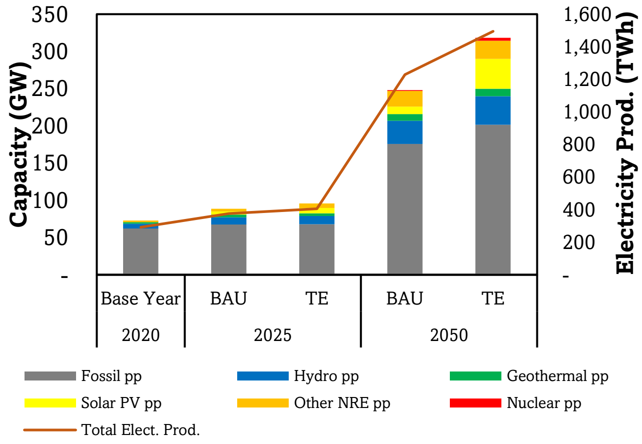
Using optimal electric vehicles and applying induction stoves for the household sector in the TE scenario will increase NRE use in the power plant sector and reduce oil and LPG usage in the transportation and household sectors. Hence, the role of NRE will increase sharply to 23.09% in 2025 and 31.33% in 2050, as shown in Figure 6. This is the same as the provisions in NEP Article 9, which states that the role of NRE will be at least 23% in 2025 and at least 31% in 2050, provided that they are economically fulfilled.

Increased use of renewable energy sources would have numerous positive effects, including stimulating the economy and creating new job opportunities, decreasing reliance on energy imports (Ulrike Lehr, 2017), fostering sustainable growth in rural areas (Clausen & Rudolph, 2020);(Potrč *et al.*, 2021), improving people's health (Ferroukhi *et al.*, 2016);(Potrč *et al.*, 2021) and lowering greenhouse gas emissions and air pollution (Potrč *et al.*, 2021). Transitioning to a greener and more efficient energy system in Indonesia would also improve energy supply security (Azzuni *et al.*, 2020);(Potrč *et al.*, 2021).

3.4 Power sector profile

To put it another way, the government is making a concerted effort to reduce its reliance on coal by increasing the proportion of NRE in the electrical sector. In Indonesia, there is an abundance of choice when it comes to the generation of power from renewable sources of energy. Solar photovoltaics, hydropower, geothermal energy, and biomass are the most prominent potentials that have the potential to be further developed in Indonesia.

In the TE scenario, the renewable capacity grows to 28.14 GW in order to meet the NRE goal of 23% by 2025, which is part of the national energy policy. Included are hydropower (11.17 GW), solar power (7 GW), geothermal power (3.58 GW), and other NRE (6.39 GW), which includes biomass, wind, biogas, and a waste-to-energy plant. In 2050, the system's capacity will reach 318.38 GW, with 116.93 GW coming from NRE (shown in Figure 7). This means that the national energy policy's NRE goal of 31% would be met. Solar power (40 GW) and hydropower (38.47 GW) would make up most of the new and renewable electricity capacity. Geothermal power (10 GW) would be next, and the rest, 24.45 GW, would come from other NRE, with 18.67 GW coming from biomass power. Co-firing biomass with coal in power plants would use 10.88 million tons of biomass in 2025 and 36.35 million tons in 2050. In the Java-Bali or West Kalimantan systems, nuclear power plants with a capacity of 1 GW are expected to be built in 2035. By 2050, a total of 4 GW of nuclear power will be in place. By 2025, 23% of the General Plan of National Energy (RUEN)'s electricity will be renewable. Renewable energy power plants will account for 45.2 GW of the 135.5 GW total capacity in 2025. With 167.6 GW from NRE, the RUEN's 2050 target is 443.1 GW.



Note : Other NRE include biomass, wind, biogas, and waste to energy plant

Fig. 7 Power sector profile

The national energy program's 31% NRE objective will be met. The target of the RUEN power plant's installed capacity is higher than our study results. Due to RUEN's strong economic growth forecasts, which average 7.36 percent from 2020 to 2050, the COVID-19 pandemic has been considered in our research, resulting in a 3.72 percent average yearly growth rate between 2020 and 2050.

It is further noticed from Figure 7 that, under the TE scenario, the total amount of electricity produced in 2050 would amount to 1,494.76 TWh. The generation mix would consist of fossil fuels (62.07%) and NRE sources (37.93%), such as hydro (14.26%), other NRE sources (10.25%), solar (5.86%), geothermal (5.55%), and nuclear (1.95%).

Indonesia possesses forty percent of the world's geothermal resources, with infinite resources and reserves of 23,766 MWe and reserves of at least 14,422 MWe (KESDM, 2021). Geothermal development has been hindered by high-risk exploration, forestry permission requirements, and tariff disputes. Only a minor portion of the entire proven reserves, or 2,130.7 MW, had been consumed by 2020 (KESDM, 2021). Furthermore, geothermal power plants take several years to develop during the discovery phase. It takes a minimum of seven years for a conventional geothermal power station in Indonesia to begin generating electricity (Maulidia *et al.*, 2019), which is why only 10 GW of geothermal power will be developed in 2050—much less than the 40 GW of solar power.

Wind and solar power have gotten cheaper to the point where they are increasingly being used in new power plant construction (Burke *et al.*, 2019). Recent studies by IRENA show that the global weighted average LCOE (levelized cost of electricity) for photovoltaics on a large scale dropped from USD 0.381/kWh in 2010 to USD 0.057/kWh in 2020, a drop of 85%. Utility-scale solar PV is now competitive with the least-priced new fossil fuel-fired capacity thanks to a considerable drop in costs. Onshore wind farms have contributed to a 56% drop in the global weighted average price of power over the same time period, from USD 0.089/kWh to USD 0.039/kWh (IRENA, 2021).

The Indonesian MEMR (Ministry of Energy and Mineral Resources) estimates a 208 GW solar energy potential, of which only about 0.07% has been exploited thus far (Barran & Setiawan, 2022). Solar power is one of the most effective means to reach the goal of using a larger share of green energy sources. Indonesia is constructing PV roofs, solar farms, and floating solar with an installed capacity target of 37.15 GW (Barran & Setiawan, 2022). In addition, according to the findings of our research, solar power results in a rapid capacity expansion, reaching 40 GW by 2050, which is more than 30 GW higher than the BAU scenario. Meanwhile, in the TE scenario, wind power is expected to have a small role, growing to 2.5 GW by 2050. On average, around the globe, Indonesia is one of the countries with the least amount of wind. As a result, wind power is not now at the forefront of Indonesia's efforts to change its energy system (Langer *et al.*, 2022).

In addition, under the TE scenario, hydropower reaches 38.47 GW, with mini-hydropower contributing 30%, pumped hydro energy storage providing 18%, and large hydropower accounting for the remaining 7%. Delivering power when demand is high and storing it when generation is high, pumped storage hydropower can guarantee the stabilization of the electrical grid and the energy time-shifting of renewable energy intermittency (Ali *et al.*, 2021). The relocation of many villages is a necessary social cost for large hydropower projects. In light of this, the development of large-scale hydro projects will require additional time and effort to adhere to tighter social and environmentally friendly requirements (Maulidia *et al.*, 2019). Expanding biomass-based power facilities is met with similar and more overt obstacles. To generate power through biomass combustion, a large area of land will be required for the cultivation of biomass raw materials (Maulidia *et al.*, 2019). On the other side, small-scale power plants that run off of local biomass can be constructed, and these plants can then be positioned close to demand centers on Indonesia's many islands. Biomass resources include things like residual forest waste, cultivation of woody and non-woody biomass, animal waste, wastewater, and urban solid waste (Wahono *et al.*, 2022). In this study, biomass power reaches 18.67 GW in the TE scenario and 16.35 GW in the BAU scenario. This is a 12% increase in installed capacity.

In particular, nuclear power is seen as a low priority by the Indonesian government, which has labeled it an "option of last resort." Accordingly, the energy market in Indonesia is not currently receiving any nuclear power supplies. Indonesia continues to exhibit interest in nuclear power despite the fact that it is not a primary policy choice. This is due to nuclear power being a carbon-free electrical option (Cho *et al.*, 2021). Based on the results, the first 1 GW of nuclear power would be put in place in 2035, and by 2050, the total would reach 4 GW.

A small portion of the National Energy Council (DEN) seems to be against building nuclear power plants, but the majority of the council has agreed to start nuclear development soon because it will help reduce emissions and make sure there is enough energy for everyone (Maulidia *et al.*, 2019).

Due to the high ownership rates of electric vehicles and induction stoves, additional power plant capacity is required to meet the increased electrical demand. It is anticipated that there will be an extra 89.05 GW of power plant capacity in 2050 as a result of these programs, with 55.29 GW coming from NRE and the remainder from fossil fuel power plants. The direct emissions of carbon dioxide and other pollutants into the air from road transportation can be greatly diminished if electric vehicles are widely adopted. In Indonesia, where coal-fired power plants are prevalent, the demand for electric vehicles could increase CO_2 emissions. In such cases, the environmental advantages of electric vehicles will not be completely achieved (European Environment Agency, 2016).

Coal-fired power plants are still the most popular way to generate electricity, mostly due to their low cost and ability to provide a continuous supply. The outcomes of this study indicate that throughout the transition period, fossil fuels are still used, but they are gradually replaced by a more sustainable renewable energy system. Nonetheless, this transitional period must be meticulously planned in order to meet energy demand while ensuring environmental sustainability (Maulidia *et al.*, 2019).

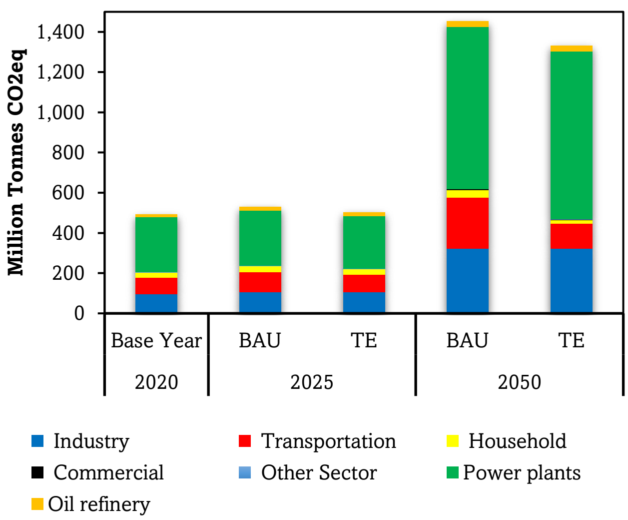
3.5 Greenhouse Gas Emission

GHG emissions will result from the use of fossil fuels and commercial biomass to meet the BAU and TE scenarios. The power, transportation, and industrial sectors are the top three contributors to greenhouse gas emissions by sector in 2050. The percentage of the power plant sector will exceed fifty percent, followed by the industrial and transportation sectors (twenty percent each), the residential sector and oil refinery (two percent each), and the commercial and other sectors (one percent each). Due to the electric vehicle and induction stove programs on the demand side and NRE deployment on the supply side, total GHG emissions for the energy sector in 2050 decrease from 1,428.47 million tonnes CO_{2eq} under the BAU scenario to 1,332.4 million tonnes CO_{2eq} under the TE scenario, as shown in Figure 8.

Carbon dioxide is released into the atmosphere during the burning of fossil fuels and the making of cement. The combustion of solid, liquid, and gaseous fuels, in addition to gas flaring, are all major contributors to this category of emissions (The World Bank, 2020). Numerous factors, including economic and demographic factors, technical advancements, institutional frameworks, ways of life, and international trade, influence carbon dioxide emissions (Kachoee *et al.*, 2018). According to the World Bank, carbon dioxide emissions per capita in the world in 2020 were 4.5 metric tonnes, with a 0.85% increase from 1999 to 2019 (The World Bank, 2020).

Figure 9 displays projected GHG emissions per capita from energy activities, showing that this number will decrease from 4.48 tonnes CO_{2eq} /capita in 2050 under the BAU scenario to 4.1 tonnes CO_{2eq} /capita in the case of the TE scenario, where high effect mitigation action such as NRE has been largely implemented.

As can be seen in Figure 9, the two scenarios' emission projections are nearly identical up until the year 2023. Beginning in 2023, when more aggressive mitigation steps are put into place, the trajectories begin to diverge from the BAU trajectory. In 2025, under the TE scenario, the proportion of new and renewable energy in the entire national energy mix would rise to 23%; by 2050, it would rise to 31%; this shift would lead to lower GHG emissions per capita.



Note : Not considering fugitive oil & gas and fugitive mining
Fig. 8 GHG emission in the energy sector

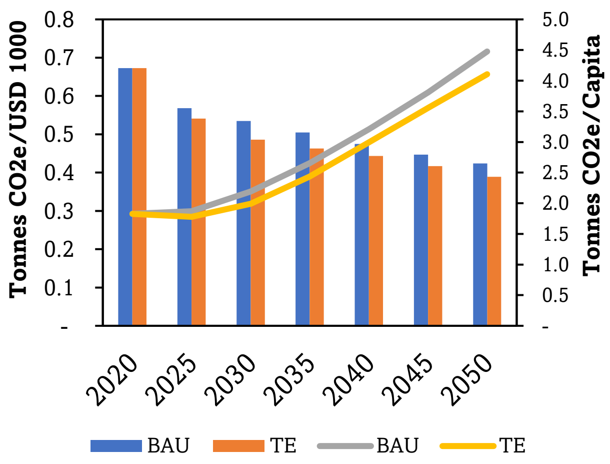


Fig. 9 GHG emissions per capita and per GDP

Moreover, despite a 6% increase in global carbon dioxide emissions and GDP in 2021, the average emissions intensity of global economic output remained unchanged at 0.26 tonnes of CO_{2eq} per $1000 of GDP (IEA, 2022). Meanwhile, GHG emissions per GDP in Indonesia would continue to fall under the BAU and TE scenarios, from 0.67 tonnes of CO_{2eq} per $ 1000 in 2020 to 0.42 tonnes of CO_{2eq} per $ 1000 and 0.39 tonnes of CO_{2eq} per $ 1000 in 2050, respectively.

4. Policy Implications

This paper analyzes the impact of Indonesia's energy transition pathway through the electrification of end-use sectors and the decarbonization of power generation. Under the Energy Transition (TE) scenario, the NRE mix in 2025 and 2050 would reach 23% and 31%, respectively, of the total national energy mix, with significant energy savings in the transportation and household sectors. Solar power, hydropower, biomass power, geothermal power, and nuclear power would dominate Indonesia's electrical mix in the foreseeable future. In addition, a rise in electricity production from NRE would have a beneficial effect on the environment. Either GHG emissions per capita or GHG emissions per GDP might be lowered by 7% under the TE scenario compared to the BAU scenario.

The results of this research can be used as a basis for creating policies that will make Indonesia's NRE sector more sustainable. These policies should be able to address issues relating to social factors, the economy, technology, and government that get in the way of NRE implementation. (Moorthy *et al.*, 2019).

Social barriers to renewable energy include not having enough skilled workers and buying up land that could have been used for farming, tourism, etc. A big problem with solar farms is that they need a huge amount of land to make the same amount of energy that a small coal-fired power plant can make (Moorthy *et al.*, 2019). The average amount of land needed for one solar module is about 2 m^2, so it is expected that it will be hard to find the land needed in the future (Barran & Setiawan, 2022). Indonesia has come up with floating solar on hydropower dams, solar power on land that used to be mined, and solar power on roofs as ways to deal with land problems.

The high initial investment required, the paucity of financial institutions, the rivalry with fossil fuels, and the lower level of subsidies available in comparison to conventional fuels are all factors that contribute to the economic and financial challenges faced (Moorthy *et al.*, 2019). An Agency for the Management of Environmental Funds, known as BPDLH (Badan Pengelola Dana Lingkungan Hidup), was set up by the Indonesian government to break budget limits and ensure financial support for protecting and managing the environment, including taking steps to stop and adapt to climate change. Carbon trading, soft loans, traditional grants, environmental subsidies, and government viability gap funding (VGF) support are the sources of money controlled by BPDLH (Wahono *et al.*, 2022).

Technology has also impeded the adoption of NREs. Problems include not having enough of the right technology, not knowing how to use and maintain it properly, not being able to do research and development, and the exorbitant expense of the technology (Sambodo *et al.*, 2022);(Moorthy *et al.*, 2019). As a result, the government must place a greater emphasis on renewables research and development in order to improve the technological capabilities of local renewables producers and, ultimately, lower renewable energy prices (IESR, 2018). In addition, the absence of a smart grid that integrates conventional and renewable energy sources and the restricted role of research and development in energy storage technologies are regarded as technological obstacles (Sambodo *et al.*, 2022). This prospective smart grid technology will promote access to healthier, cleaner, and more long-lasting resources (Elrahmani *et al.*, 2021), whereas the development of an energy storage system appears to be one option for addressing the intermittent nature of solar energy (Wattana & Aungyut, 2022).

Regarding regulatory impediments, inefficient government policies, inadequate economic incentives, and administrative and bureaucratic difficulties have hampered the rapid expansion of renewable energy (Moorthy *et al.*, 2019). Therefore, for a nation's sustainable development, effective regulatory rules within the energy business are essential, and cooperation between different agencies should be strengthened. Thus, Indonesia needs national leadership that consistently exhibits a strong political commitment to encourage and support renewable energy.

As a reference price, the government published a regulation based on the regional and national main production cost of generating power (BPP). The rule doesn't take into account tariff increases, which are demanded by private investors to offset future inflation (Maulidia *et al.*, 2019). By developing Feed-in-Tariff (FiT) policies that favor renewable energy and are also adaptable to changes in technology and market conditions, it is possible to dismantle this unhelpful legislation (IESR, 2018).

The period of 2021–2022 can be considered an important milestone for the development of NRE. To date, the government has issued several essential regulations: the energy ministry's regulation no. 26/2021 in terms of rooftop solar power systems; the Business Plan for the National Electricity Supply from 2021–2030 (Putriastuti & Fitriyanti, 2022); the President of the Republic of Indonesia's Regulatory Order 112/2022 on the Fast Development of Renewable Energy Sources for Electricity Production (GoI, 2022); and the harmonization of tax regulation. In Law No. 7 of 2021 Concerning the Harmonization of Tax Regulations, the government imposed a carbon tax (UU HPP). Article 13 of the HPP Law governs, among other things, the carbon tax imposed on carbon emissions that harm the environment (Suryani, 2022). Initially, the implementation of carbon trading, including the imposition of a carbon tax, was targeted for April 1, 2022, with a cap and trade and tax scheme. However, the policy's implementation was postponed due to inadequate infrastructure.

The study implies that NREs like solar power, hydropower, biomass power, geothermal power, and nuclear power are all potentially feasible possibilities for the generation of electricity. It is possible that the NRE will be able to have a big effect on the economic, social, and environmental sustainability of the energy industry. Solar energy, hydropower, biomass, geothermal energy, and nuclear power are just a few of the alternative energy sources that will play a significant role in the continuing change. Solar energy is inexpensive because, after the initial investment, the ongoing costs of producing solar energy are typically unnoticeable. Because of its accessibility on a local level, solar power is an essential component of reliable energy sources. Then, hydropower can be paired with wind, solar, and other sources to provide affordable, reliable grid electricity. In addition to irrigation, providing water for industry and homes, preventing flooding, and creating jobs, hydropower provides energy security by making less use of fossil fuels (Kabeyi & Olanrewaju, 2022). Due to the huge potential of feedstocks in rural regions, where there is also a need to enhance access to inexpensive, dependable electricity and boost rural development, biomass power plants, like the ones on the Mentawai Islands, are a particularly appealing choice for Indonesia (Wong, 2021). Biomass power plants can have a steady supply of feedstock for a long time if they use planting strategies that take into account both the community and nature. This is a way to encourage the construction of biomass power plants across the country (Wahono *et al*., 2022), which according to this study, are projected to reach 18.67 GW by 2050. In addition, the most significant obstacle that geothermal electricity generation must overcome is the lengthy period of time required for project development, the high risks involved in the beginning of the process, and enormous expenditures for conventional systems, which also have poor efficiency in the process of converting electricity. Geothermal power plants could be built faster and with less risk if they were wellhead power plants (Kabeyi & Olanrewaju, 2022).

The use of nuclear power has a number of environmental benefits, the most important of which is that its greenhouse gas emissions during its entire lifecycle, including those associated with uranium mining and processing, are nearly equal to those of sustainable power plants. Because of this, using nuclear power more will lead to less pollution and less damage to the environment (Kabeyi & Olanrewaju, 2022).

5. Conclusion

Indonesia's NRE goals are important because they show that Indonesia is aware of NRE as a possible way to get more people on the power grid, make sure there is enough power, and reduce environmental damage. In line with Rule No. 79 of 2014 from the government on the National Energy Policy, under the TE scenario, the renewable capacity grows to 28.14 GW to meet the national energy policy's NRE target of 23% by 2025. This includes 11.17 GW of hydropower, 7 GW of solar power, 3.58 GW of geothermal power, and 6.39 GW of other NRE (biomass, wind, biogas, waste-to-energy plants). In 2050, the system's capacity will reach 318.38 GW, with 116.93 GW coming from renewable and nuclear energy. This means that the national energy policy's NRE goal of 31% would be met. By the end of the study, the capacity of solar power would have grown from almost nothing to more than 216 times its current level. Hydropower's capacity would have increased by more than six times from its current level of 6.14 GW in 2020, while geothermal and biomass power capacities would have increased by over 5 times and more than 10 times, respectively.

Some renewable power plants, like solar and wind power, can only supply power for short periods of time. For a steady supply, these plants would need to be connected to a baseload power supply system, like hydropower plants or nuclear power plants. Also, energy storage is a key part of a sustainable energy system because it helps solve the problem of intermittent renewable energy sources. Pumped-storage hydroelectricity and BESS (Battery Energy Storage System) are two ways to store energy. Also, GHG emissions per capita are expected to drop from 4.48 tonnes CO2eq/capita in 2050 under the BAU scenario to 4.1 tonnes CO2eq/capita under the TE scenario if high-impact mitigation actions like NRE have been mostly put into place. In the meantime, GHG emissions per $1000 of GDP would fall from 0.42 tonnes CO2eq per $1000 under the BAU scenario to 0.39 tonnes CO2eq per $1000 under the TE scenario in 2050.

Solar power, hydropower, geothermal power, biomass, and nuclear power could all be important parts of Indonesia's future power mix. Nevertheless, in the short to medium term, coal-based transformations may be required before moving on to a more sustainable low-carbon energy source. This phase of change needs to be carefully planned so that energy needs are met while environmental impacts are kept to a minimum.

The implementation of low-carbon development is hindered by the social, economic, technological, and regulatory obstacles that are crucial to the acceleration of NRE deployment. For the deployment of new and renewable energy to be successful, big problems like a lack of skilled workers, land issues, expensive initial capital, not enough money for R&D, and ineffective government regulations should be dealt with as soon as possible.

Future research might concentrate on removing coal from the electricity sector as a way to get global carbon dioxide (CO2) emissions to zero by 2050. When it comes to new coal power plants that have a long life ahead of them, thinking about a CCS (Carbon Capture and Storage) retrofit in the future could be a good way to avoid the power plant's almost full depreciation.

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