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Abstract: An analysis of fuel demand has been conducted on the optimization results of Indonesia's generating system development planned, covering the study period from 2022 to 2060. This study aims to calculate fuel demands from existing and committed power plants, as well as the optimized electricity system plan. This includes a wide range of fuel types, such as coal, natural gas, fuel oil, gasoil, industrial diesel oil (IDO), liquefied natural gas (LNG), nuclear, biomass, biogas, wind, solar, hydropower, geothermal, ocean energy, and municipal waste. Analysis has been done using the supply-demand optimization model of the Low Emission Analysis Platform (LEAP) tool. LEAP provides the option to utilize either bottom-up or top-down methodologies, or a combination of both, for demand modeling, allowing for increased flexibility. On the supply side, LEAP offers a comprehensive suite of functionalities encompassing accounting, simulation methodologies, and optimization modeling, including the simulation of fuel demand calculations. This research employs two scenarios: Business-as-usual (BAU) without new renewable energy and energy conservation policies, and Net Zero Emission (NZE) with these policies and no fossil fuel use in committed plants. The total fuel demand calculated for the 2022-2060 period in the BAU scenario is 75,089.46 Million Barrel of Oil Equivalent (MBOE), consisting of 56,550.53 MBOE (75.31%) from fossil fuels and 18,538.93 MBOE (24.69%) from new renewables. In contrast, the NZE scenario demands 78,049.30 MBOE, with 33,372.12 MBOE (42.76%) from fossil fuels and 44,677.18 MBOE (57.24%) from new renewables. Therefore, BAU remains dominated by fossil fuels, while NZE achieves dominance by new renewable energy.

Keywords: fuel demand analysis; sustainable electricity power system; Net Zero Emission; New Renewable Energy; Indonesia

1. Introduction

The electricity demand in Indonesia in 2022 reached 299.2 TWh met by power generation with an installed capacity of 83.8 GW. Most of the power generation still relies on fossil energy, whether from coal power plants (46.0 GW), gas power plants (17.9 GW), or oil power plants (7.3 GW), constituting a total share of 85% of the overall power generation. The remaining 12.6 GW is derived from renewable energy sources[1]. Indonesia's share of renewable energy in installed power capacity remains lower compared to other ASEAN member states[2].

The government has promised under the Paris Agreement to cut greenhouse gas emissions by using more renewable energy, including for power generation. Updated and included in the 2022 Enhanced Nationally Determined Contribution (ENDC) document submitted to the UNFCCC is this commitment. By 2030, Indonesia wants to have cut greenhouse gas emissions by 31.89% on its own or 43.20% with help from other countries[3].

Despite the significant potential of renewable energy for power generation in Indonesia reaching 3,686 GW[4], there are still numerous challenges in implementation, particularly regarding the high investment costs. This potential needs to be evaluated and mapped out as part of the energy transition process toward net zero emission (NZE) by 2060, as outlined by the government[5,6]. Various low-carbon technologies will gradually contribute and replace fossil-based power generation technologies in the long term.

The National Energy Policy (Kebijakan Energy Nasional, KEN) of Indonesia outlines a plan for the country's energy consumption until 2050. Renewable Energy Law (Law No. 21/2014) mandates the development and use of renewable energy sources, including geothermal, hydro, solar, and wind, to reduce dependence on fossil fuels. Energy and Mineral Resources Ministerial Regulation No. 50/2017 targeted by 2025, it is expected to account for at least 23% of the energy mix, and by 2050, it is expected to reach a minimum of 31%, provided that the economy is satisfied.

According to KEN, the national energy development prioritizes four principles: (a) Optimize the usage of renewable energy sources, taking into account economic factors; (b) Reduce the reliance on petroleum; (c) Optimize the utilization of natural gas and other emerging energy sources.; (d) Employ coal as the principal energy source on a national scale[7)]. KEN's aims to drive the country towards net zero emissions by utilizing new and renewable energy sources. However, the implementation of this policy has faced various challenges and changes along the way[8)].

The National Energy General Planning (Rencana Umum Energi Nasional, RUEN) serves as a directive for national energy management. RUEN predicts that in 2025, NRE will make up 92.3 million tonnes of oil equivalent (MTOE), representing 23.0% of the overall energy supply of 400 MTOE. By 2050, the overall energy supply is expected to reach 1012 MTOE, with primary and renewable energy sources contributing 315.7 MTOE (31.2%) of the total. Therefore, a total generation capacity of 136 GW in 2025 and 443 GW in 2050 is necessary to meet the per capita electricity demand of 2,500 kWh in 2025 and 7,000 kWh in 2050, respectively. Hence, in order to fulfill the NRE mix objective outlined in the KEN, it is anticipated that the electrical supply capacity derived from NRE sources will amount to around 45.2 GW in 2025 and 167.7 GW in 2050[9)].

Consistent with these regulations, numerous studies have been carried out in Indonesia to analyze the demand and supply of energy, as well as to optimize sustainable energy development. Environmental aspects are also taken into account, particularly focusing on the reduction of greenhouse gas emissions by integrating novel renewable energy sources. The studies covered a number of issues, including nationwide coverage such as: (a) Forecasting Indonesia's energy demand through 2060[10)], (b) Analyzing the political landscape and procedures of regional energy planning in Indonesia[11)], (c) Analyzing the economic and environmental effects of reducing carbon emissions in Indonesia's power sector[12)], (d) Investigating the role of nuclear power facilities in Indonesia's journey to achieve net zero emissions by 2060[13)], (e) Utilizing power sector optimization modeling to formulate strategies for attaining low-carbon goals[14)], (f) Investigating the factors influencing electricity demand across various sectors in Indonesia[15)], (g) Formulating strategies and guidelines for renewable energy utilization in Indonesia's sustainable development[16)], (h) Collecting techno-economic data and hypothesizing for future energy system modeling in Indonesia[17)].

Additionally, the studies also focus on provincial level and grid systems, such as: (a) Prediction of Power Demand (2021-2050) in the West Kalimantan Electric System[18)], (b) Enhancing the utilisation of emerging renewable energy sources in West Kalimantan[19)], (c) Development and planning of renewable energy for an island province in North Maluku[20)], (d) An examination of the environmental implications of energy generating in Java[21)], (e) Long-term demand forecasting using an artificial neural network method for the Java-Madura-Bali electricity system[22)], (f) Reducing the carbon footprint of the Sumatra region's electricity grid through the use of nuclear and renewable energy sources[23)].

Previously, Kuncoro et al. have also conducted research nearly to the topic of this paper for the provincial and grid system levels, such as: (a) Fuel demand analysis for the Planning Development of the Jawa-Madura-Bali (JAMALI) Electricity System[24)] and (b) Analysis of fuel demand in West Kalimantan[25)].

Given the aforementioned commitments, policies, and ongoing sustainable energy research in Indonesia, the authors analyzed fuel consumption to optimize the development planning of sustainable electricity power systems in Indonesia from 2022 to 2060. The novelty of this research is modeling the fuel demands of power generators to achieve NZE in 2060. This research result is hoped to support the planning and implementation of national energy policies toward NZE.

The primary goal of the study on optimizing sustainable electricity development in Indonesia to achieve net zero emissions by 2060 is to identify and implement strategies for transitioning from fossil fuels to renewable energy. It aims to analyze current and future fuel demands in the electricity sector and create plans for the optimal integration of renewable energy sources, resulting in a reliable and efficient system that meets growing energy needs and reduces greenhouse gas emissions. Additionally, the study seeks to guide policymakers in creating supportive regulations and policies, promote energy security by reducing reliance on imported fossil fuels, and ensure the sustainability of energy resources for future generations. It also aims to attract investments from public and private sectors and encourage technological innovation in renewable energy, helping Indonesia reach its net zero emission targets by 2060.

1.1 Tools of Energy Modelling

Energy system analysis evaluates the entire energy system, from resources to end users, in an integrated way. Optimizing the electricity production process is vital for integrating renewable energy sources. This ensures efficient deployment of technologies and identifies suitable energy supplies and power generation systems.

These efforts support a sustainable energy mix, system reliability, and future electricity needs. Since 2017, various modeling tools for energy simulation and optimization have been summarized in Table 1.

Table 1. The Comparison of Energy Modelling.

No.	Model	Developer	Method	Scope
1	Compare Options For Sustainable Energy (COMPOSE)[26,27]	Morten Blarke, Aalborg University	Acounting, Mixed Integer Programming	Techno-economic energy-project assessment model
2	EnergyPlan[28]	Sustainable Energy Planning Research Group - Aalborg	Simulation / Optimization	Simulates and Optimizes the operation of a national energy system for each hour of a given year
3	Low Emission Analysis Platform (LEAP)[28–30]	Stockholm Environment Institute	Accounting / Simulation / Optimization	Integrated Energy / Environment Analysis
4	MARKet Allocation Model (MARKAL)[28,31,32]	IEA - ETSAP	Optimization	Integrated Energy / Environment Analysis
5	Energy Modelling Laboratory -Generation (EMLab-Generation)[27,33]	TU Delft - Richstein, Chappin, Bhagwat & de Vries	Agent - Based Simulation	Investment Decision Support
6	The Open Source Energy Modelling System (OSeMOSYS)[34]	KTH - Howells et al.	Linear Programming	Integrated Energy Planning
7	PLEXOS Integrated Energy Model (PLEXOS)[27,35]	Energy Exempler - Glenn Drayton	Optimization	Integrated Energy Planning
8	The Integrated MARKAL-EFOM System (TIMES)[36]	IEA - ETSAP	Optimization	Integrated Energy / Environment Analysis
9	The General Algebraic Modelling System (GAMS)[37,38]	GAMS Development Corporation	Optimization	Energy Planning

However, the energy demand projection calculations for the TIMES program are executed externally, utilizing software such as MAED or other driven energy demand projection calculations.

GAMS software is still not user-friendly, particularly for people unfamiliar with programming languages. To utilize both products, users must purchase a license. Another restriction of GAMS software is that it requires other software tools to view results, that code development is required, and that each optimization solution has its own pricing.

LEAP can be utilized to monitor energy consumption, production, and resource extraction across all economic sectors. It can account for greenhouse gas (GHG) emissions sources and sinks in both the energy and non-energy sectors. Besides tracking GHGs, LEAP can also be employed to evaluate emissions of local and regional air pollutants, widely utilized for conducting climate change mitigation assessments and integrated energy analysis, explores the effects of different approaches to electricity development on system costs and greenhouse gas emissions. LEAP can be integrated with either the Open-Source Energy Modeling System (OSeMOSYS) or the Next Energy Modeling system for Optimization (NEMO) depending on user requirements [39]. The LEAP model is capable of supporting various modeling methodologies (top-down, bottom-up, and hybrid) using different projection methods such as time series, econometrics, end-use, and stock turnover.

1.2 LEAP Advantages

LEAP optimization is accomplished by a demand-driven approach, in which the quantity of energy demand determines the energy supply mix and kind of power plant. Energy demand predictions can be readily calculated in LEAP software by providing input data in the form of macroeconomics and many quantifiable assumptions. The amount of energy required to be produced must then be projected, which is decided by historical data on energy needs in the industrial, transportation, residential, and commercial sectors, as well as high-efficiency technology input. To optimize the power generation system, a more detailed electricity demand projection is performed per end-user sector, and the amount of capacity and electricity production that will be generated, as well as the type of power plant that will be used, will be determined based on the LEAP optimization results. LEAP output can take the form of directly visible charts, tables, and graphs, as well as user-friendly data entry and processing[40]. Aside from that, this software may be immediately connected to Microsoft Excel, which is commonly used by many people to examine findings in the form of graphs and charts. The most important thing is that LEAP can be used for free by users, but there is a fee for using the NEMO Optimizer.

2. Methodology

2.1 LEAP Integrated Energy Model for Fuel Demand Analysis

LEAP uses a linear programming approach to optimize power plants with a model structure as shown in Fig. 1.

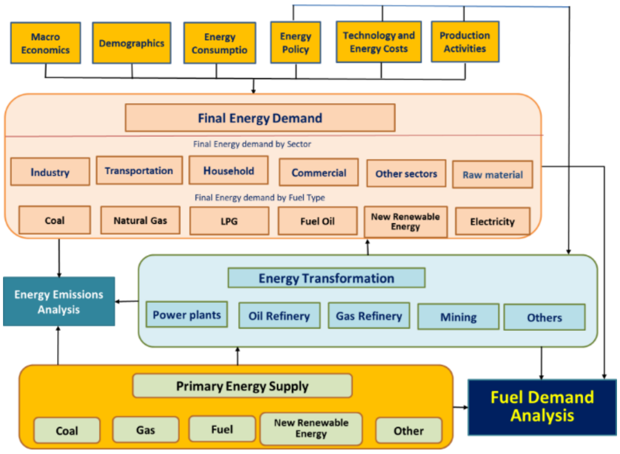

Fig. 1: LEAP analytical framework : Energy Supply and demand for Power Generation.

Annual electricity generation must be sufficient to meet annual electricity demands. The objective function utilized in optimization for this study is the minimization of total generation costs. Net present value (NPV) is utilized to represent the entirety of generation expenses. This value comprises capital costs, fixed O&M costs, variable O&M costs, and petroleum costs. In general, developing countries utilize a 10% discount rate, thus this assumption can be used to examine fuel consumption forecasts in this study[41,42]. The formula for the objective function is represented by Equation (1)[43,44].

$$Total\ Discounted\ Cost = \sum_t [\frac{1}{(1+d)^t} \sum_p [annualized\ capital\ cost_{p,t} + (fixed\ O\&M\ cost_{p,t} * capacity_{p,t}) + (variable\ O\&M\ cost_{p,t} * generation_{p,t}) + (fuel\ cost_{p,t} * generation_{p,t})]] \quad (1)$$

The variable t represents the year, whereas the variable p represents the type of generator. The optimization process in power plants necessitates data on the electricity consumption patterns on the demand side, commonly referred to as a load curve. The load curve in Indonesia exhibits an irregular distribution, characterized by distinct peak load, follower load, and base load segments. The variable p represents the type of power plant.

Multiplying fuel consumption by the emission factor for each fuel derived from the Technology and Environmental Database (TED) yields the greenhouse gas (GHG) emissions calculated in LEAP. LEAP's TEDs currently incorporate every single one of the emission factors that have been established by the Intergovernmental Panel on Climate Change (IPCC). Equation 2[45] is used to compute GHG emissions for each power plant (PE).

$$PE_{p,t} = \sum_j [EC_{p,j,t} * EF_{j,t}] \quad (2)$$

Where EC is the fuel consumption for power plant p and fuel j, and EF is the fuel j emission factor in year t. In addition to measuring CO_2 emissions, LEAP also calculates CH_4 and N_2O emissions by determining their mole values. The Global Potential for CH_4 to CO_2 equivalent is 28, while the Global Potential for N_2O to CO_2 equivalent is 265. Under the Net Zero Emissions (NZE) scenario, the overall greenhouse gas (GHG) emissions are progressively restricted on an annual basis until they ultimately reach net zero emissions by the year 2060.

To forecast energy requirements, one must consider the energy intensity and activities necessary within a given sector. Various sectors, including industrial, transportation, residential, and commercial energy consumers, will implement the utilized technology. The utilization of technology will be contingent upon the equipment's efficacy as well as the quantity and nature of fuel employed. To determine the ultimate energy requirements of the user sector, the subsequent equation (3) should be utilized[46]:

$$E_{s,t} = A_{s,t} * I_{s,t} \quad (3)$$

where E represents electricity consumption, s represents each sectoral energy in year t, A represents consumer activity, and I is the energy intensity of technology use. This equation is employed in all user sectors, including industry, transportation, residential, commercial, and others. Electricity consumption is calculated using the same equation for each user sector's electricity-based technology. In addition to determining the quantity of cars, the vehicle stock equation (4):

$$E_{transport,t} = S_{transport,t} * \frac{D_{transport,t}}{C_{transport,t}} \quad (4)$$

where C represents specified energy consumption, E represents the electricity demand for electric vehicles, S represents the number of vehicles, D denotes the distance covered per vehicle type, and transport pertains to the transportation sector. This equation applies to every land vehicle.

2.2 Scenarios, Data and Assumptions

In this study, modeling scenarios are classified into two categories: BAU scenarios and NZE scenarios. BAU scenario is a situation where basic assumptions about population and economic growth are used. It also means that the government does not make any new decisions about sector energy policy. The new energy policy and programs that go with it are just following a long-term trend. The new policy doesn't control the growth of technology in any area of the economy, including power generation, transportation, industry, homes, businesses, and retail. Instead, it lets the market do its thing.

Meanwhile, the NZE scenario applies assumptions related to strategies for achieving Net Zero Emission (NZE), such as the gradual phasing-out of power plants that use coal or other fossil fuels like gas and oil, speeding up the development of renewable energy plants like solar, wind, geothermal, hydro, etc., using best available technology (BAT) to save energy more, driving electric vehicles (EVs), and cooking with electricity, natural gas, and DME instead of LPG. Infrastructure development for green hydrogen, green ammonia, and nuclear power plants is also taking place, as is the usage of carbon capture and storage (CCS)/carbon capture utilization and storage (CCUS), as well as the improvement of the regional electricity transmission system.

Both the BAU scenario and the NZE scenario use the economic and technical data provided by Santosa et al. (2023) from government and private sector stakeholders[43]. Moreover, it employs the demographic and economic growth assumptions obtained from data provided by BPS (Indonesian Central Bureau of Statistics)[47] and Bappenas (National Development Planning Agency)[48] as presented in Table 2.

The fundamental assumptions employed in both scenarios are:

1. The population growth projection for Indonesia is based on a study conducted by BPS. According to the study, the average national growth rate is projected to be 1.01% per year at the start of the projection year, gradually decreasing to 0.1% by the end of the projection year in 2060. Additionally, the study predicts that the urban population share will increase from 59% in 2025 to 75.5% in 2060.
2. The GDP growth forecasts from Bappenas studies show that the economy will grow by an average of 5.7% per year, starting with 5.44% per year growth in 2025 and then rising until it reaches a peak of 7.00% in 2035. At the end of the estimated year, it drops to 4.00% per year after that. It is thought that sectoral GDP share forecasts will follow trends based on data on how sectors have affected national GDP in the past. The sectoral energy demand forecasts depend a lot on the share of GDP because each sector uses energy in different ways, which can be seen in the different energy intensities.
3. Key metrics and indicators to measure fuel demand and sustainability in electricity development over the 2022-2060 period include total energy consumption, fuel mix, electricity demand growth rate, peak load demand, energy intensity, and efficiency of power plants for fuel demand; and greenhouse gas emissions, renewable energy share, carbon intensity, energy storage capacity, grid reliability and stability, investment in renewable energy, policy and regulatory support, public and private sector investment, energy access, and technological innovation for sustainability. Additionally, economic impacts such as cost of electricity and job creation, environmental impacts like land and water use, and social impacts including public health, energy equity, and community engagement will also be assessed.

Table 2. Assumption of Socio-Economic Indicator.

Indicators/ Year	Population (Million People)	Population Growth (%)	GDP (Trillion Rupiah)	GDP Growth (%)
2021[50]	270.2	1.16	11,710	5.31
2025	288.4	1.01	13,720	5.44
2030	297.4	0.82	18,282	6.50
2035	308.4	0.66	25.405	7.00
2040	317.2	0.51	34,639	6.00
2045	324.1	0.37	45,079	56,310
2050	328.1	0.25	56,310	4.25
2055	332.1	0.15	68,840	4.00
2060	334.1	0.10	83,754	4.00

Source: BPS[47] and BAPPENAS[48].

3. Result and Discussion

3.1 Electricity Demand Projection

Based on Scenario-BAU, the electrical energy demand in Indonesia in 2022 is around 326.08 TWh and is projected to keep on increasing to reach around 1,886.20 TWh in 2060. In 2022, the composition of electrical energy demand is based on its user sectors comprising the industrial sector at around 43.12%. followed by the household sector at around 35.66%, the business sector (examples include office services, hotels and restaurants, financial services, and social services, etc) at around 21.11%, and the transportation sector at around 0.11%. Meanwhile, for the electrical energy demand projection in 2060, the composition of electrical energy demand is based on its user sectors comprising the industrial sector at around 41.27%. followed by the household sector at around 28.29%, the business sector at around 20.62%, the transportation sector at around 9.12%, and the electrolysis process input sector for green hydrogen production at around 0.70%. Consider the idea that infrastructure and economic readiness for green hydrogen production can only be accomplished by 2035 and an electrolysis process is needed for the production process. The result of the projection of electricity demand based on Scenario-BAU is shown in Fig. 2.

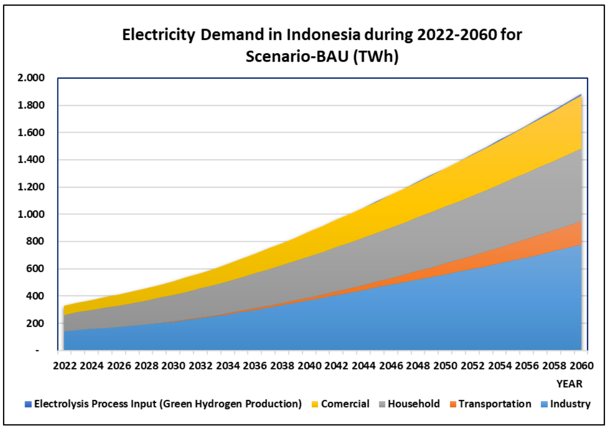

Fig. 2: The Electricity demand projection in Indonesia during 2022-2060 under Scenario BAU.

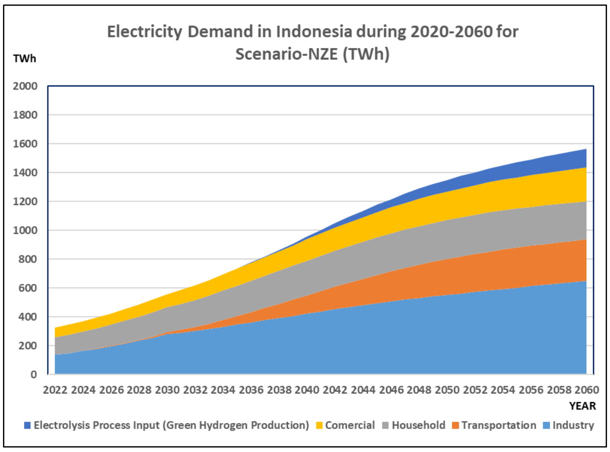

Fig. 3: The Electricity demand projection in Indonesia during 2022-2060 under Scenario NZE.

Based on Scenario-NZE, the electrical energy demand in Indonesia in 2022 is around 326.08 TWh and is projected to keep on increasing to reach around 1,564.33 TWh in 2060. In 2022, the composition of electrical energy demand is based on its user sectors comprising the industrial sector at around 43.12%. followed by the household sector at around 35.66%, the business sector at around 21.11%, and the transportation sector at around 0.11%. Meanwhile, for the electrical energy demand projection in 2060, the composition of electrical energy demand is based on its user sectors comprising the industrial sector at around 41.48%. followed by the transportation sector at around 18.46%, the household sector at around 16.83%, the business sector at around 14.92%, and the electrolysis process input sector for green hydrogen production at around 8.31%. The green hydrogen production projection will be started in 2035. The result of the projection of electricity demand based on Scenario-NZE is shown in Fig. 3.

3.2 Projection of power generation mix and electricity production in Indonesia during 2022-2060

The optimization simulation has been carried out for Scenario-BAU and Scenario-NZE, which shows that the power generating capacity increases by adding various types of power plants annually. As a result under Scenario-BAU, the peak load in 2022 is around 82.43 GW, and it will rise to 428.36 GW in 2060. This figure also shows the Scenario-BAU simulation result for the optimization on the generation expansion planning in Indonesia with the cumulative configuration projection of capacity plants at 2060 as follows: Coal PP (163.59 GW), Coal PP-CCS (5.34 GW), Gas PP (0.90 GW), Oil PP (1.16 GW), Gas CC-PP (66.51 GW), Gas Fired PP (8.08 GW), Gas Engine PP (21.74 GW), Diesel PP (5.37 GW), Hydro PP (15.87 GW), M-M Hydro PP (1.84 GW), Hydro PS (5.10 GW), Geothermal PP (7.38 GW), Biomass PP (1.82 GW), Biogas PP (4.46 GW), M Waste PP (1.20 GW), Solar PP (84.43 GW), Wind PP (16.49 GW), and BESS (17.09 GW). Based on Scenario-BAU, in 2060, the power plants from fossil will dominate to fulfill the energy demand, namely around 63.66%, meanwhile, the contribution of the new renewable energy power plant is around 32.35%, and BESS is around 3.99%.

Meanwhile, as a result under Scenario-NZE, the peak load in 2022 is around 82.43 GW, and it will rise to 515.09 GW in 2060. This figure also shows the Scenario-NZE simulation result for the optimization on the generation expansion planning in Indonesia with the cumulative configuration projection of capacity plants at 2060 as follows: Coal PP-CCS (38.02 GW), Hydro PP (30.54 GW), M-M Hydro PP (3.36 GW), Hydro PS (4.23 GW), Geothermal PP (20.03 GW), Biomass PP (22.03 GW), Biogas PP (10.46 GW), M Waste PP (7.35 GW), Solar PP (227.76 GW), Wind PP (64.95 GW), Ocean PP (1.39 GW), Nuclear PP (21.75 GW), and BESS (63.23 GW). Based on Scenario-NZE, in 2060, the power plants from new renewable energy will dominate to fulfill the energy demand, namely around 80.34%. The power plants that have the greatest impact on fulfilling energy requirements are Solar Power Plants and Wind Power Plants. Other side, the contribution of the fossil power plant (namely Coal PP with CCS) is around 7.38%, and BESS is around 12.27%.

The growth rate of electricity generation capacity at BAU is 4.08% per year, while at NZE it is 4.46% annually. The projected generating capacity at BAU is lower than at NZE because NZE is dominated by NRE-based power plants which have a lower capacity factor than fossil-based power plants. The electricity production from the installed electrical capacity to satisfy the electricity demands of user sectors is depicted in Fig. 4.

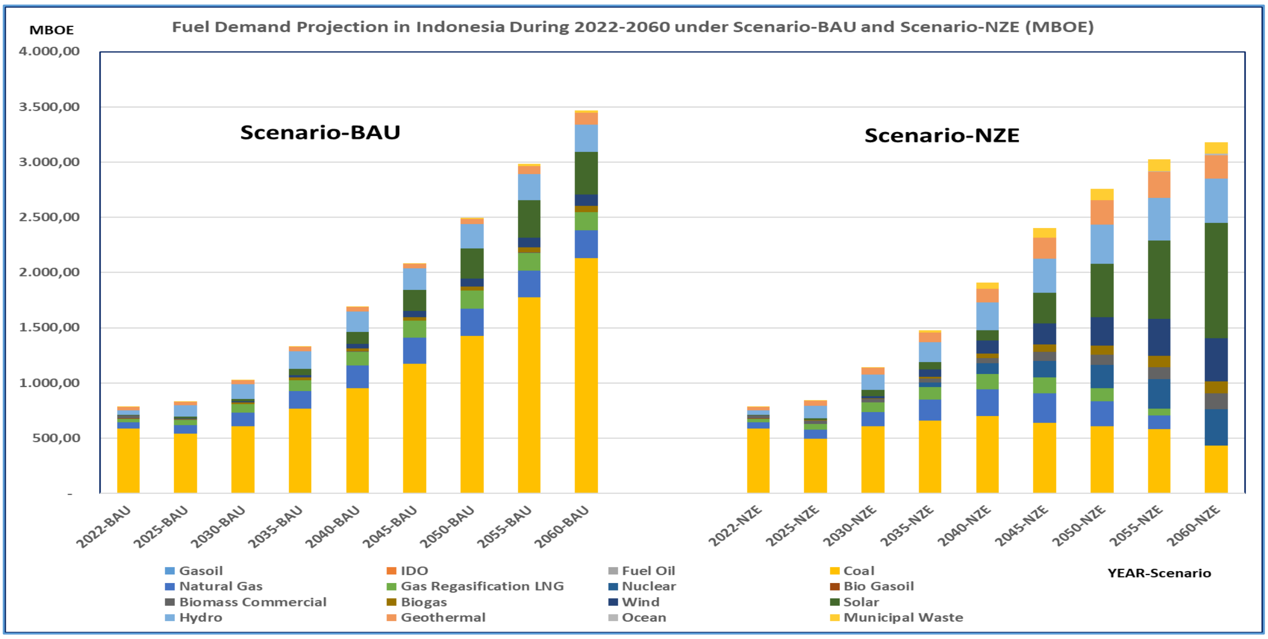

Fig. 4: The computation of the aggregate fuel demand in Indonesia from 2022 to 2060, considering Scenario-BAU and Scenario-NZE.

The BAU Scenario predicts that electricity production will increase at a rate of 4.52% annually between 2022 and 2060. In contrast, the NZE Scenario indicates a growth rate of 4.99% from 2022 to 2051. However, from 2051 to 2060, the growth rate has decelerated to 0.75% annually, and subsequent developments have transpired. The growth rate in Scenario-NZE is attributable to the declining contribution of coal-fired power facilities (without CCS), which will reach zero by 2060.

The uncertainty that occurs in this modelling is approached by applying two scenarios based on different assumptions including government policy regarding the termination (phase-out) of coal – fired power plants, fuel substitution in the transportation sector, the development of new and renewable energy technology which is predicted to become cheaper and the entry on new technologies such as CCUS and hydrogen technology.

3.3 Fuel Demand of Power Generation Analysis in Indonesia During 2022-2060

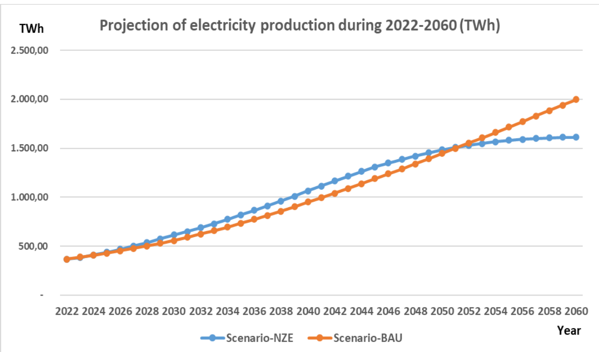

Fig. 5: The Projection of electricity production in Indonesia during 2022-2060 under Scenario-BAU and Scenario-NZE.

The total fuel demand calculation per year (for 2022, 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060) in Indonesia is shown in Fig. 5 with an annual average growth rate of about 4.09 % for Scenario-BAU and about 3.92 for Scenario-NZE.

The result of the total fuel demand calculation during the study period 2022-2060, for Scenario-BAU is 73,134.75 Million Barrel of Oil Equivalent/MBOE (consists of fossil fuel: 54,905.27 MBOE (75.31%) and new renewable energy: 18,229.47 MBOE (24.93 %)). Meanwhile, the result of the total cumulative fuel demand calculation, for Scenario-NZE is 78,049.30 MBOE (consists of fossil fuel: 33,372.12 MBOE (42.76 %) and new renewable energy: 44,677.18 MBOE (57.24 %)). Therefore, Scenario-BAU is still dominated by fossil fuels, meanwhile, Scenario-NZE is dominated by new renewable energy.

Mardiana et al.[49] forecast the highest electricity demand to reach 1,800 TWh by 2060, emphasizing urbanization, economic growth, and increased household electricity consumption. Another study by Liun et al.[50] forecasts electricity demand at 1,500 TWh by 2050, driven by aggressive electrification in the transport and industry sectors, reflecting the potential for significant electric vehicle adoption.

Under the NZE scenario, overall fuel demand remains relatively high. This can be attributed to the substantial growth in electricity demand within the transportation sector, where the growth rate of conventional vehicle conversion to electric vehicles is projected to continue increasing until 2040. Consequently, electricity demand will continue to be relatively high. The industrial sector also has a large demand for electrical energy due to the use of electric-powered industrial equipment.

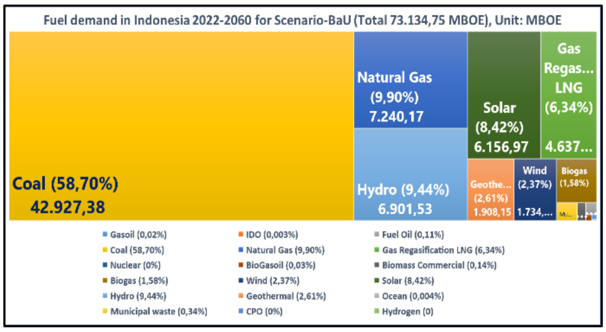

Fig. 6: The aggregate fuel requirement for electricity generation from 2022 to 2060.

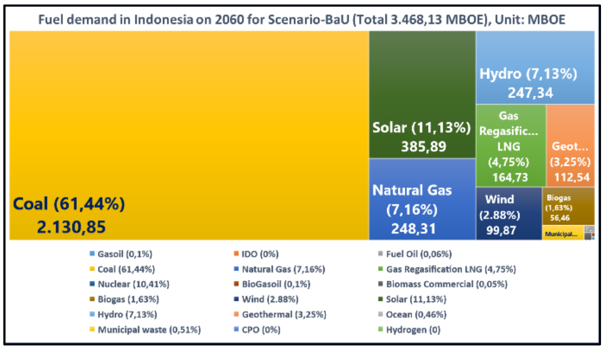

Fig. 7: The aggregate fuel requirement for electricity generation in 2060 in Indonesia under Scenario-BAU.

Figure 6 shows the cumulative total calculation of fuel demand under Scenario-BAU in Indonesia during the period 2022-2060, namely 73,134.75 MBOE, which consists of a coal (58.70%), natural gas (9.90%), hydro (9.44%), solar (8.42%), gas regasification LNG (6.34%), wind (2.37%), geothermal (2.61%), biogas (1.58%), municipal waste (0.34%), commercial biomass (0.14%), fuel oil (0.11%), bio-gasoil (0.02%), gasoil (0.02%), and IDO (0.003%). It can be seen here that in the Scenario-BAU during the 2022-2060 period, the total demand for fossil fuels (namely coal, natural gas, and gas regasification LNG) dominates to meet electricity energy needs in Indonesia.

Figure 7 shows the total calculation of fuel demand under Scenario-BAU in Indonesia in 2060, namely 3,468 MBOE, which consists of coal (61.44%), solar (11.13%), natural gas (7.16%), hydro (7.13%), gas regasification LNG (4.75%), geothermal (3,25%), wind (2.88%), biogas (1.63%), municipal waste (0.51%), fuel oil (0.06%), biomass commercial (0.05%), bio-gasoil (0.01%), and gasoil (0.01%). In this scenario, Coal power plants without CCS will have a total installed capacity of 163.59 GW in 2060. In contrast, coal power plants with CCS will be added to the electricity system in 2060, with a total installed capacity of 5.34 GW.

Figure 8 shows the cumulative total calculation of fuel demand under Scenario-NZE in Indonesia during the period 2022-2060, namely 78,049 MBOE, which consists of coal (29.81%), solar (14.67%), hydro (12.78%), natural gas (8,20%), wind (7.80%), nuclear (6.19%), geothermal (6.98%), gas regasification LNG (4.58%), biomass commercial (3.30%), municipal waste (2.92%), biogas (2.48%), fuel oil (0.15%), ocean (0.10%), bio-gasoil (0.03%), and gasoil (0.02%). The entire need for fossil fuels and new renewable energy fuels looks to be balanced in the Scenario-NZE during the 2022-2060 period to meet Indonesia's electrical energy needs.

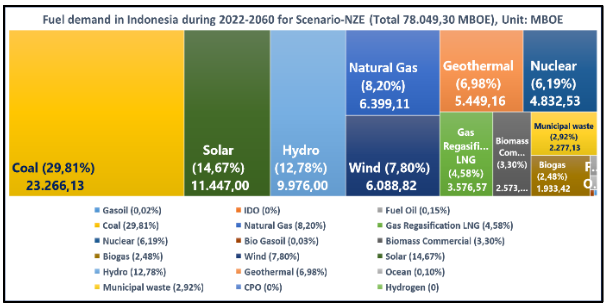

Fig. 8: The fuel consumption during the period 2022-2060.

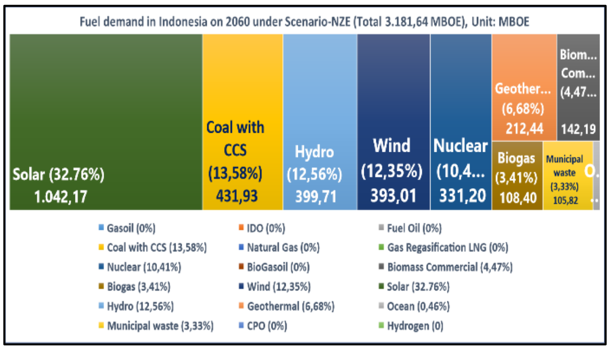

Fig. 9: The fuel consumption in 2060 in Indonesia under Scenario-NZE.

The fuel demand calculation for Indonesia in 2060, as depicted in Fig. 9 amounts to 3,182 MBOE. This figure includes the following sources: solar energy (32.76%), coal with CCS (13.58%), hydroelectric (12.56%), wind (12.35%), nuclear (10.41%), geothermal (6.68%), commercial biomass (4.47%), biogas (3.41%), municipal waste (3.33%), and the ocean (0.46%). By 2060, there will be 5.34 GW of coal power plants with CCS installed cumulatively, compared to nil (0%) for coal power stations without CCS. Based on the results above, by accelerating the development and provision of new and renewable energy, energy supply issues in remote areas can be resolved.

The IEA roadmap[6], which focuses on Indonesia's transition to net-zero emissions by 2060, states that a significant shift towards renewable energy sources is expected, with solar and wind contributing nearly 70-80% of electricity generation by 2060. Coal usage is projected to decline drastically, with its share in total electricity generation reducing significantly by mid-century.

Emerging technologies play a vital role in optimizing sustainable electricity development in Indonesia by boosting efficiency, reliability, and environmental sustainability. Renewable energy sources, such as solar, wind, and geothermal, decrease reliance on fossil fuels and reduce greenhouse gas emissions, aligning with

Indonesia's commitment to minimizing its carbon footprint. Energy storage systems, including batteries, address the intermittency of renewable energy, ensuring a steady and reliable power supply. Smart grid technologies enable efficient energy distribution, real-time monitoring, and demand response, facilitating better integration of renewable sources and enhanced grid management. Collectively, these technologies support Indonesia's objective of creating a more sustainable and resilient energy infrastructure.

3.4 Reducing CO2 Emission from Electricity Power Generations.

The BAU-Scenario indicates that the existence of existing power plants will increase carbon dioxide (CO2) emissions from 366.40 million tons in 2022 to 1,323.56 million tons in 2060, as depicted in Fig. 7. Meanwhile, the strategy aimed at reducing CO2 emissions in the NZE-Scenario will result in a decrease in emissions from the electrical sector in Indonesia. According to the NZE-Scenario, the presence of renewable power plants will decrease carbon dioxide emissions from 366.40 million tons in 2022 to zero emissions in 2060. This will be achieved by incorporating new renewable energy power plants and coal power plants equipped with carbon capture and storage (CCS) technology.

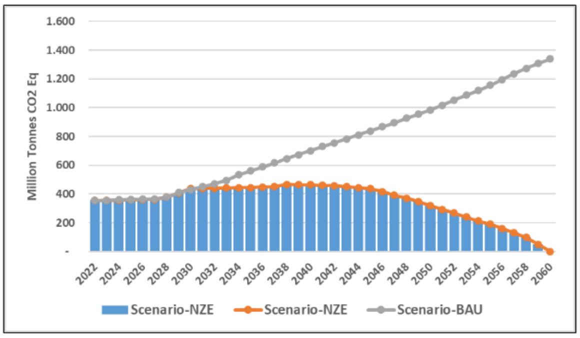

Fig. 10: Power generating emission based on Scenario-BAU and Scenario-NZE.

Figure 10 shows that without special actions to reduce the use of fossil fuels and coal, as seen in the BAU scenario, CO_2 levels would continue to rise until 2060. As a result, fulfilling the government's goal of eliminating emissions is impossible unless efforts are made to replace traditional coal power plants and programs to conserve energy in various sectors. In the NZE scenario, CO2 emissions in 2040 will begin to decline and will continue to decline due to numerous initiatives undertaken in this scenario, such as the implementation of CCS and CCUS in power plants that use coal or other fossil fuels and the gradual replacement of coal-fired power plants and other fossil fuel power plants (e.g., gas and oil) with renewable energy power plants (e.g., solar, wind, geothermal, water, and so forth). Other efforts are constructing infrastructure for green hydrogen, green ammonia, and nuclear power plants. Furthermore, there are plans to transition conventional vehicles to electric vehicles, and utilizing electricity, natural gas, or DME as an alternative to LPG to power cooking equipment are additional initiatives.

The transitioning to NZE will significantly benefit society by improving air quality and health, reducing long-term energy costs due to decreased fossil fuel dependency, and creating new job opportunities in the renewable energy sector, thereby enhancing energy security through diversification. For the government, this transition necessitates the formulation and implementation of supportive policies and regulations, increased investment in renewable energy infrastructure, and potential collaboration with private and international sectors for financing.

The Ministry of Environment and Forestry has the task of carrying out monitoring, reporting, and validation (MRV) for national-scale GHG emissions. This report contains plans and efforts to reduce GHG emissions for the UNFCCC in the form of a Nationally Determined Contribution (NDC) in accordance with the commitments in the Paris Agreement[3)]. Periodic assessments and reviews of progress towards achieving the net-zero target must be conducted, including evaluations of policy effectiveness, the pace of renewable energy adoption, and emission reduction initiatives. These reviews may be carried out every 2-5 years, aligning with Indonesia's climate targets and international commitments.

In Indonesia, optimizing sustainable electricity development involves crucial roles from various stakeholders: Government bodies formulate and enforce policies, set renewable energy targets, and ensure environmental compliance; Private sector companies invest in and advance renewable technologies, driving innovation and commercialization; and Civil society advocates for environmental protection, raises awareness, and engages in community projects to ensure that the transition addresses social equity and local needs.

4. Conclusion

1. Indonesia's electricity consumption in 2022 was roughly 326.08 TWh and is expected to continue rising to reach nearly 1,886.20 TWh in 2060 under the Scenario-BAU, and 1,564.33 TWh in 2060 under the Scenario-NZE. The predicted amount of power use based on Scenario-NZE is lower compared to Scenario-BAU because Scenario-NZE has considered the use of equipment with the most energy-efficient technology in the industry, household, and business sectors. Meanwhile, demand in the transportation sector increased, due to the use of electric vehicles.
2. Analysis of total fuel demand calculation during 2022-2060 shows that Scenario-BAU is still dominated by fossil fuel, namely 75,089.46 MBOE (consists of fossil fuel: 75.31% and new renewable energy: 24.69 %). Meanwhile, the result of the total fuel demand calculation, for Scenario-NZE is

78,049.30 MBOE (consists of a new renewable energy: 57.24 %, and fossil fuel: 42.76 %).

3. The analysis of total fuel demand calculation at the end of the study (2060) reveals the continued dominance of fossil fuels in the BAU scenario. The total demand reaches 3,468.13 MBOE, with fossil fuels comprising 73.42% and new renewable energy contributing 26.58%. Conversely, the Net Zero Emission (NZE) scenario achieves a lower total demand of 3,181.64 MBOE. Here, new renewable energy sources account for a substantial 86.42%, while fossil fuels (specifically coal with CCS technology) play a minor role, contributing only 13.58%.
4. New-renewable energy (NRE) resources (including sun, wind, hydro, biomass, biogas, geothermal, ocean, and nuclear fuel of uranium) have significant potential in Indonesia. Based on the results of the analysis carried out, there is no doubt that efforts to utilize new and renewable energy sources to replace coal and fossil fuels will be able to reduce emissions according to the target. Undoubtedly, this potential will bolster Indonesia's dedication to transforming the energy sector in order to accomplish the goals outlined in the Agenda for Sustainable Development and the Paris Agreement.
5. The fuel demand analysis for a sustainable energy power system from 2022-2060 is crucial for Indonesia's goal of reaching net-zero emissions. This comprehensive analysis serves as a foundational guide for strategic decision-making, policy formulation, and investment planning within the energy sector.
6. By 2060, the development of electricity in Indonesia is expected to have transformative impacts on both its people and government. The transition to renewable energy, the electrification of sectors like transportation, and improvements in energy infrastructure will drive economic growth, reduce environmental harm, and provide more equitable access to energy. However, the Indonesian government will face substantial challenges in managing the affordability of energy, ensuring energy security, and navigating the complexities of transitioning away from fossil fuels. The success of these efforts will depend on strong policies, technological innovation, and international cooperation.
7. This research recommends strategies to overcome implementation barriers like financial constraints, technological limitations, and public acceptance by formulating policy incentives to attract investment in renewable energy, fostering international cooperation for technology transfer and funding, promoting technological innovation through R&D, and conducting public awareness campaigns with active community participation.
8. The success of implementing sustainable electricity development strategies can be measured by the increase in the number of renewable energy power plants, the rise in GDP as an economic impact of reduced fossil fuel consumption, the improvement in air quality due to the application of CCUS (Carbon Capture, Utilization, and Storage), and the reduction in the burning of oil and coal.

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