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Impact Analysis of NZE Scenarios on National Energy Supply Using LEAP

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ABSTRACT — The achievement of the national energy supply target based on new and renewable energy (NRE) by 2025, as stated in the National Energy Policy, is still far below expectations. This shortfall is due to the continued fossil energy dominance in all sectors. To achieve net zero emission (NZE) targets by 2060, systematic and consistent transitions from fossil fuels to NRE are essential. The fossil energy utilization (domestic and imported) is expected to decline, while the substitution with NRE will increase. This study aimed to provide a forecast analysis of national energy supply and utilization across various sectors, including household, industry, power generation, transportation, and commercial sectors, until 2060. The analysis used energy modeling simulations with business as usual (BAU) and NZE scenarios, conducted using the Low Emission Analysis Platform (LEAP) software. LEAP is an integrated, scenario-based energy model used to determine energy demand, production, and resource extraction across all economic sectors. The simulation results for the NZE scenario indicate significant reductions in fossil energy usage across all sectors compared to the BAU scenario, with an increase in NRE utilization, especially in the power generation sector. By 2060, domestic coal, natural gas, fuel oil, and liquefied petroleum gas supplies are projected to decrease by 81%, 74%, 87%, and 84%, respectively; meanwhile, the demand for petroleum remains unchanged. Overall, the supply of NRE under the NZE scenario is expected to grow by an average of 9% per year from 2019 to 2060, amounting to 2.3 times the supply in the BAU scenario.

KEYWORDS — Energy Supply, Net Zero Emissions, Low Emission Analysis Platform, New Renewable Energy.

I. INTRODUCTION

With the ongoing development across various sectors, economic and population growth, along with energy needs, are also continuously rising. Consequently, energy supply is a crucial factor in fostering a country's development. To meet national energy needs, both domestically produced energy and imported energy are utilized, including fossil fuels and new and renewable energy (NRE) sources.

The G20 conference held in Bali in November 2022 set a target of achieving carbon neutrality in line with the 2015 Paris Agreement. As the host, Indonesia encourages both developed and developing countries to accelerate the energy transition towards net zero emissions (NZE) by 2060. This involves shifting from fossil fuels to energy sources that do not produce carbon emissions by increasing the share of NRE across all sectors. Indonesia needs to immediately transition to NRE, considering that fossil energy reserves continue to decrease every year. Energy transition efforts to achieve NZE require a gradual process with a long duration [1]. The energy transition in Indonesia is heavily influenced by the country's economic conditions, requiring significant costs and economic stability [2]. As of 2021, the national energy supply mix is dominated by fossil fuels at 87.8%, consisting of coal (37.6%), petroleum (33.4%), and gas (16.8%), with NRE accounting for only 12.2%. The target set by the National Energy Policy for NRE to constitute 23% of total primary energy by 2025 is unlikely to be met. Despite Indonesia's vast NRE potential of 3,686 GW, a comprehensive utilization strategy is essential to achieve the NZE target by 2060.

Global energy development has shifted from fossil fuels towards improving energy efficiency and developing NRE sources, primarily aiming to reduce greenhouse gas (GHG) emissions. Numerous studies have conducted long-term energy projections and developed scenarios to support the transition to renewable energy. Research spanning from 2012 to 2050, involving 139 countries, indicates that all energy-consuming sectors will rely on NRE in the future [3].

The Low Emission Analysis Platform (LEAP) energy modeling simulation is extensively used to predict national energy supply and utilization data. LEAP is increasingly being adopted to support government policies on energy system modeling, thanks to its ability to integrate energy projections with environmental impacts [4]. Many studies have analyzed energy projections in various countries using LEAP. One such study in Thailand indicates that to achieve the GHG emission reduction target of 20% by 2030, Thailand must meet at least 50% of its renewable energy plan targets and 75% of its energy efficiency plan targets, or vice versa [5]. In addition, if extended to 2050, the nationally determined contributions (NDC) scenario indicates a potential reduction of 30.4% compared to the business-as-usual (BAU) scenario.

The Pakistan study simulated the country's electricity system from 2016 to 2040 across five scenarios: BAU, coal scenario (CS), gas scenario (GS), nuclear scenario (NS), and renewable scenario (RS). The results indicate that while the RS scenario has a lower production rate compared to BAU, its production cost is approximately five times lower than those of the BAU, CS, and GS scenarios [6].

Studies in Malaysia indicate that, without new policies, energy consumption in the land transportation sector is expected to increase approximately 3.7 times from 2012 to 2040. However, by implementing alternative fuel policies, such as using natural gas vehicles, energy consumption can be reduced by 25% by 2040 compared to the BAU scenario [7].

A study in Colombia identified 44 mitigation policies and actions that could reduce greenhouse gas emissions by 28% [8]. A study in Brazil examined strategies to improve access to electricity by 2050, aiming to reduce biomass consumption in the residential sector by 50% or more through a combination of grid expansion and decentralized solar panels [9]. In China, an environmental and socio-economic impact assessment study of renewable energy development in Zhangjiakou shows that GHG emissions will peak in 2030, with energy consumption 13.23% lower than the BAU scenario [10].

South Korea has developed a plan to transition to net-zero emissions by increasing the share of renewable energy and reducing energy demand. The results indicate enhanced energy security, higher employment in the power generation sector, and reduced greenhouse gas emissions [11]. Meanwhile, research in Turkey considered three scenarios for the transition to renewable energy: the BAU, energy conservation (EC), and renewable energy scenarios [12]. The EC scenario involves using energy-efficient devices and implementing a carbon tax, while the renewable energy scenario focuses on maximizing the share of renewable energy sources in electricity generation. The results indicate that the REN scenario is the optimal energy policy for Turkey in terms of cost and environmental impact [12].

In Indonesia, several projection models using LEAP have been developed. Scenarios for the Java-Bali power plant capacity expansion from 2016 to 2050 have been created to predict energy, costs, and CO_2 emissions, with a focus on NRE mix targets. Additionally, LEAP has been used to identify the optimal energy policy options for Turkey in terms of cost and environmental impact [13]. The results indicate that solar panels (photovoltaic) and wind energy are more competitive than other types of renewable energy. Additionally, the findings suggest that energy policy should prioritize the use of renewable energy and enhance the capacity of the electricity grid to accommodate changes in variable renewable energy. LEAP has been used to forecast the planning level of electricity demand in West Java [14] and determine the optimal cost path for electricity sector development on Sumatra Island [15] using a scenario design that aligns with PT PLN (Persero)'s General Plan for Electricity Supply (*Rencana Umum Penyediaan Tenaga Listrik*, RUPTL) and targets for reducing GHG emissions.

In this study, simulations using LEAP with BAU and NZE scenarios have been developed to estimate national energy supply and utilization data across all sectors, including household, industry, power generation, transportation, and commercial sectors, up to the NZE target in 2060. The results of this study are expected to provide policy insights and identify synergies and compromises associated with potential energy policies in driving the transition to renewable energy.

II. DATA AND METHODOLOGY

A. DATA

This national energy supply model utilized secondary data from reliable sources to ensure realistic and accurate optimization. The data sources included demographic and economic data from the Statistics Indonesia (Badan Pusat Statistik, BPS), energy consumption data from the Handbook of Energy and Economic Statistics of Indonesia (HEESI 2021), and natural resource potential data from the Ministry of Energy and Mineral Resources (MEMR) [16]. The book states that Indonesia has coal reserves of 17.9 billion tons, 4 billion barrels of oil, and 61 trillion standard cubic feet (TSCF) of natural gas. The national supply of coal, oil, and gas is substantial, amounting to 614 million tons, 240 million barrels, and 2,434 billion standard cubic feet (BSCF), respectively. Additionally, Indonesia has a NRE potential of 3,686 GW and an available supply of 12.24 GW. Historical data up to 2021 were used as a reference in this study to project the energy supply up to 2060.

TABLE I
PROJECTIONS OF POPULATION, HOUSEHOLD, AND URBANIZATION

Description	Unit	2020*)	2030	2040	2050	2060
Population	Million	270	294	313	324	331
Population growth	%	1.16	0.81	0.54	0.3	0.2
Household	Million	69	76	81	84	86
Urban share	%	56.4	63.4	69.9	75	77

*) Results of the Statistics Indonesia population census in 2020

Table I presents projections of Indonesia's population growth and other indicators, based on a BPS study showing an average national growth rate of 5.7% per year [17]. According to BPS data, projections of national GDP indicate that due to the COVID-19 pandemic, economic growth in 2020 will be -2.07%. However, in 2021, economic conditions are expected to begin recovering, with growth reaching 3.70% [18].

The 2021 HEESI energy source data and population projections from Table I were used to populate the Key Assumptions components of LEAP. These data were inputted in the Expression section of the BAU and NZE scenarios, utilizing the Interp function to determine values for specific years through linear interpolation.

B. METHOD

The calculation of balance and utilization of the national energy supply until 2060, including both fossil fuels and renewable energy, were analyzed using LEAP software. LEAP is an integrated, scenario-based energy model that can be used to analyze energy demand and supply, as well as their relation to GHG emissions [19]. It supports a variety of modeling methodologies, including bottom-up, top-down, and hybrid approaches [20]. LEAP has user-friendly tools and an intuitive dashboard display. The required computer specifications to run LEAP are not specifically mentioned.

The energy demand (ED) analysis employs the end-use method. The total ED was calculated by multiplying the activity level by the energy intensity, as shown in the following equation.

$$ED_{b,y} = AL_{b,y} \; x \; IE_{b,y} \quad (1)$$

Given that *ED* represents the total energy demand, *AL* denotes the activity level, *IE* stands for energy intensity (energy use per activity), while *b* and *y* correspond to the sector and year, respectively [21].

According to HEESI, energy consumption is divided into five sectors: industrial, transportation, household, commercial, and others. The projected energy consumption for each sector is calculated using different equations, as each sector has a unique definition of energy intensity [20].

$$E_{ik} = A_{ik} \times IE \quad (2)$$

$$E_r = A_r \times \frac{U}{Eff} \quad (3)$$

$$E_t = N \times \frac{D}{C} \tag{4}$$

where E_{ik} represents the energy demand of the industrial or commercial sector, E_r represents the energy demand of the household sector, and E_t represents the energy demand of the transportation sector. A_{ik} denotes the activity level of the industrial or commercial sector, while A_r denotes the activity level of the household sector. IE is the final energy intensity of the industrial or commercial sector, U is the useful energy intensity of the household sector, Eff is the efficiency of equipment, N is the number of vehicles, D is the distance traveled by vehicles, and C indicates the specific fuel consumption (SFC).

The projected number of vehicles was calculated based on the previous year's inventory, the current year's sales, and the operational lifetime of cars, buses, trucks, and motorcycles. Vehicle lifespan is associated with the survival rate and is represented by an S-curve function. The adoption of battery electric vehicle (BEV) and fuel cell electric vehicles (FCEV) also follows an S-curve function. Vehicle sales were modelled using a logistic function [22].

$$S_t = S_{t-1}\ x\ (1 + r_t) \tag{5}$$

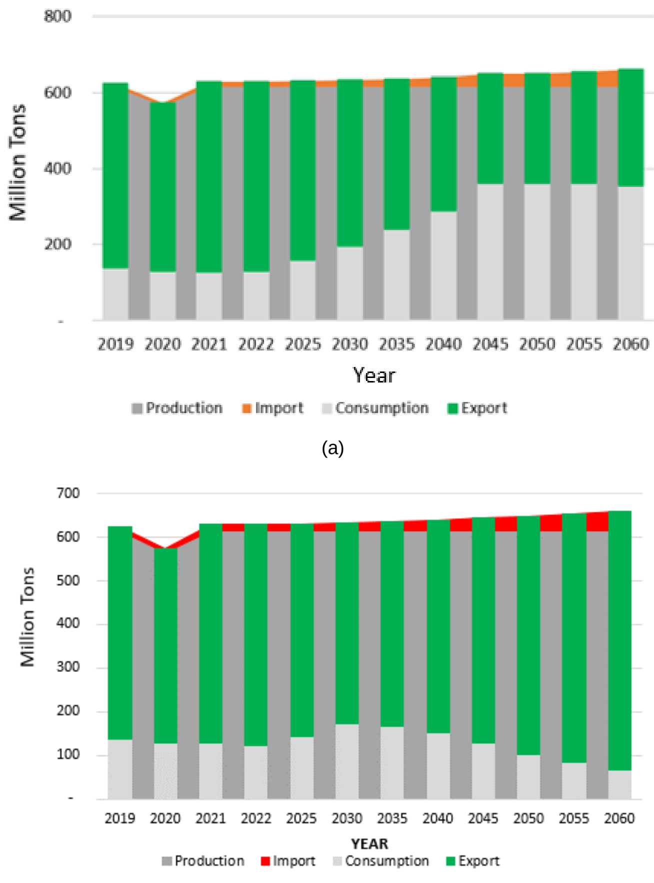
$$r_t = K_a\ x\ e^{(-K_b\,(t-1) + C_{t-1}K_c)} \tag{6}$$

given that S represents the number of vehicle sales, r denotes the growth rate of vehicle sales, t is the tth year, C indicates the growth of GDP per capita, K_a is the regulating factor for initial growth, K_b is the speed factor for reaching final growth, and K_c is the regulating factor for final growth.

This study examines two scenarios: the BAU scenario and the NZE scenario. In the BAU scenario, no new government interventions in sectoral energy policies are introduced. Instead, the energy policies and related programs in place as of the base year, 2021, remain in effect. Technological developments across all economic sectors, including industry, transportation, household, commercial, and power generation, are not governed by new policies but follow market-driven or historical trends.

Meanwhile, the NZE scenario introduces new policies and assumptions aimed at achieving net-zero emissions by 2060. These include the elimination of coal-fired power plants (*pembangkit listrik tenaga uap*, PLTU), a reduction in the construction of diesel power plants (*pembangkit Listrik tenaga diesel*, PLTD) in underdeveloped, frontier, and outermost regions, or often referred to as 3T (*terdepan*, *terluar*, *tertinggal*) regions, accelerated development of renewable energy plants, and the more intensive application of energy-saving technologies. The elimination of PLTUs does not mean the removal of their electricity infrastructure; instead, it involves transitioning to biomass and coal cofiring systems before ultimately phasing out PLTUs [23]. The proportion of biomass in cofiring with coal ranges from 5–15%, depending on biomass availability and the flexibility of plant technology [24].

Both scenarios use the same basic assumptions, such as population and economic growth, making their comparison relevant. The other assumptions include: 1) Indonesia escapes the middle-income trap (GDP of US$12,695 per capita) before 2045 [25], specifically by 2041 as targeted by the government; 2) the projected sectoral GDP share is calculated based on historical data of sector elasticity to national GDP. This GDP share is crucial for making sectoral energy demand projections, given that each sector is characterized by different consumption patterns and energy intensity.



(a)

(b)

Figure 1. Coal balance in (a) BAU scenario and (b) NZE scenario.

III. RESULTS AND DISCUSSION

A. ENERGY SUPPLY RESULTS

In analyzing the national energy supply forecast, the discussion focuses on the balance of coal, crude oil, fuel oil (*bahan bakar minyak*, BBM), natural gas, and NRE, and their utilization using LEAP software with two scenarios: BAU and NZE.

1) COAL BALANCE

The coal balance in the BAU and NZE scenarios is presented in Figure 1. It is evident that the BAU and NZE scenarios did not affect coal production and imports, but they did influence domestic coal demand and coal exports, either increasing or decreasing them. Between 2019 and 2060, coal production is projected to decline slightly by 0.01% per year, decreasing from 616 million tons in 2019 to 614 million tons by 2060. This represents a minimal overall decline. The most significant drop in coal production occurred during the COVID-19 pandemic, with output falling to 564 million tons in 2020. After that, production is expected to rebound to 614 million tons and remain stable at that level through 2060.

The BAU scenario indicates that domestic coal demand is projected to grow at an average rate of 2.3% annually, increasing from 138 million tons in 2019 to 354 million tons by 2060. This figure represents approximately 58% of the total coal production in 2060, meaning that domestic demand will remain within production limits. Consequently, surplus coal will be available for export. However, coal exports are expected

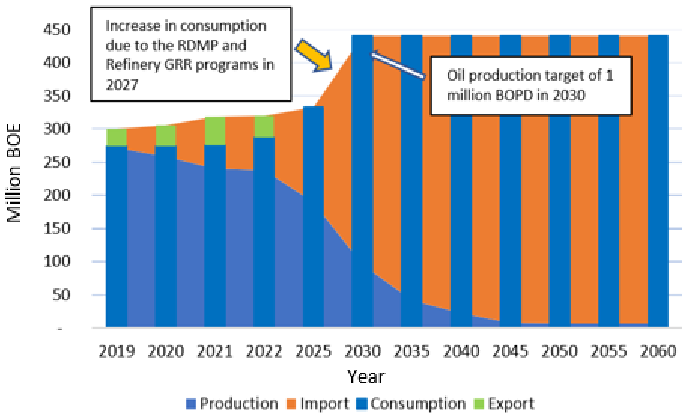


Figure 2. Petroleum balance in, BAU and NZE scenarios.

to decline by 1.1% per year, falling from 485 million tons in 2019 to 306 million tons by 2060. This decline suggests that domestic coal production will face constraints.

However, coal imports will still be necessary for the metallurgical industry, which is projected to grow at an average rate of 4.6% per year, increasing from 7 million tons in 2019 to 46 million tons by 2060. In contrast, under the NZE scenario, domestic coal supply needs are expected to decline at an average rate of 1.8% per year, falling from 138 million tons in 2019 to 66 million tons by 2060—a reduction of 81% compared to coal needs under the BAU scenario. This aligns with the NZE scenario's goal of decreasing coal use, particularly in coal-fired power plants.

From 2019 to 2060, coal production is expected to remain steady at 614 million tons. With domestic demand for coal being prioritized, the amount of excess coal available for export is projected to grow by an average of 0.5% annually, or 1.6% more than in the BAU scenario. In contrast, coal imports are anticipated to increase by an average of 4.6% per year, rising from 7 million tons in 2019 to 46 million tons by 2060 under the NZE scenario. Importing coal will remain necessary, particularly for the metallurgical industry, with a focus on coking coal.

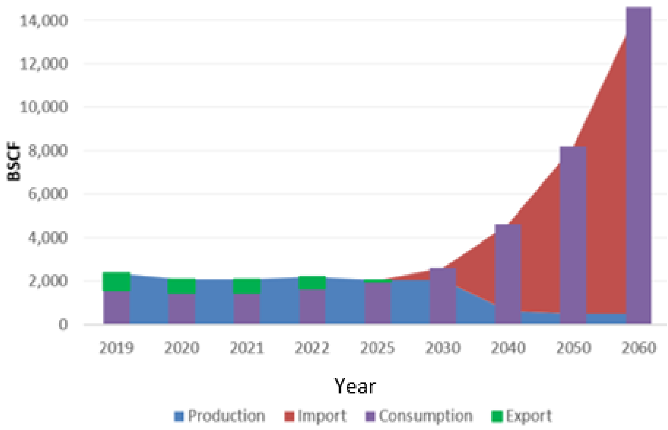
2) PETROLEUM BALANCE

The BAU and NZE scenarios did not affect petroleum production, exports, or imports. From 2019 to 2060, petroleum production is projected to decline by 9% per year. Petroleum demand is expected to rise from 274 million barrels of oil equivalent (BOE) in 2019 to 423 million BOE in 2027. This increase is driven by the expansion of refinery capacity through the Refinery Development Master Plan (RDMP) program and the construction of a new Grass Root Refinery (GRR). Furthermore, the plan to optimize petroleum production, with a target of 1 million barrels of oil per day (BOE/D) by 2030, is expected to boost demand to 440 million BOE by 2060, provided no additional refinery capacity is introduced.

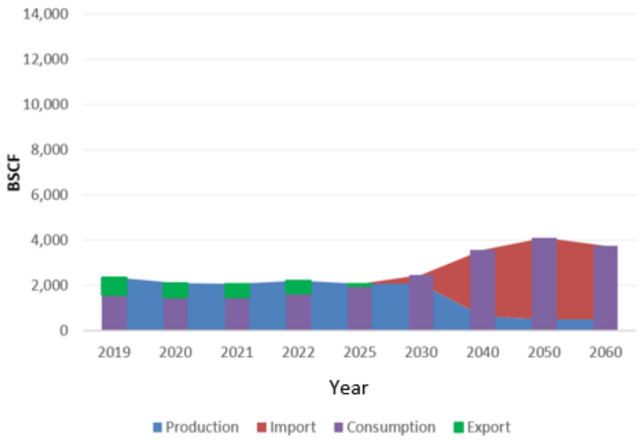
The objective is to reduce petroleum imports, which are projected to grow by 7% annually, from 28 million BOE to 434 million BOE. Crude petroleum exports are expected to continue until 2024. However, from 2024 to 2060, petroleum exports are likely to cease due to limited production and the depletion of petroleum reserves if no new reserves are discovered, as illustrated in Figure 2.

3) GAS BALANCE

Figure 3 displays the gas balances for the BAU and NZE scenarios. From 2019 to 2060, gas production is projected to



(a)



(b)

Figure 3. Gas balance in (a) BAU scenario and (b) NZE scenario.

decrease by an average of 4% per year, falling from 2,372 billion standard cubic feet (BSCF) in 2019 to 495 BSCF by 2060. This decline is anticipated due to the lack of significant new gas field discoveries.

Under the BAU scenario, natural gas demand is projected to grow significantly, with an average annual increase of 6%. This demand is expected to rise from 1,578 BSCF in 2019 to 14,612 BSCF by 2060. Excess production will be exported until 2026, after which no further gas exports are anticipated. Despite an additional natural gas program planned for 12 BSCF in 2030, this will not be sufficient to meet the rising domestic demand. Consequently, natural gas imports will be necessary, with an anticipated average annual increase of 16% from 2027 to 2060.

The NZE scenario for 2060 is projected to reduce the demand for natural gas by 74% compared to the BAU scenario. Despite a decrease in natural gas production and a halt in exports, imports remained necessary to address the shortfall in supply. However, gas imports decreased significantly, by 77% compared to the BAU scenario in 2060. Natural gas supports the transition to clean energy by facilitating the use of NRE [26].

4) SUPPLY OF NEW RENEWABLE ENERGY (NRE)

Figure 4 illustrates the supply of NRE under both BAU and NZE scenarios. Over the 2019 to 2060 period, overall NRE is projected to grow at an average rate of 6% per year under the BAU scenario, increasing from 23 million tons of oil equivalent (MTOE) in 2019 to 288 MTOE by 2060. During this period, solar power generation (*pembangkit listrik tenaga surya*, PV)

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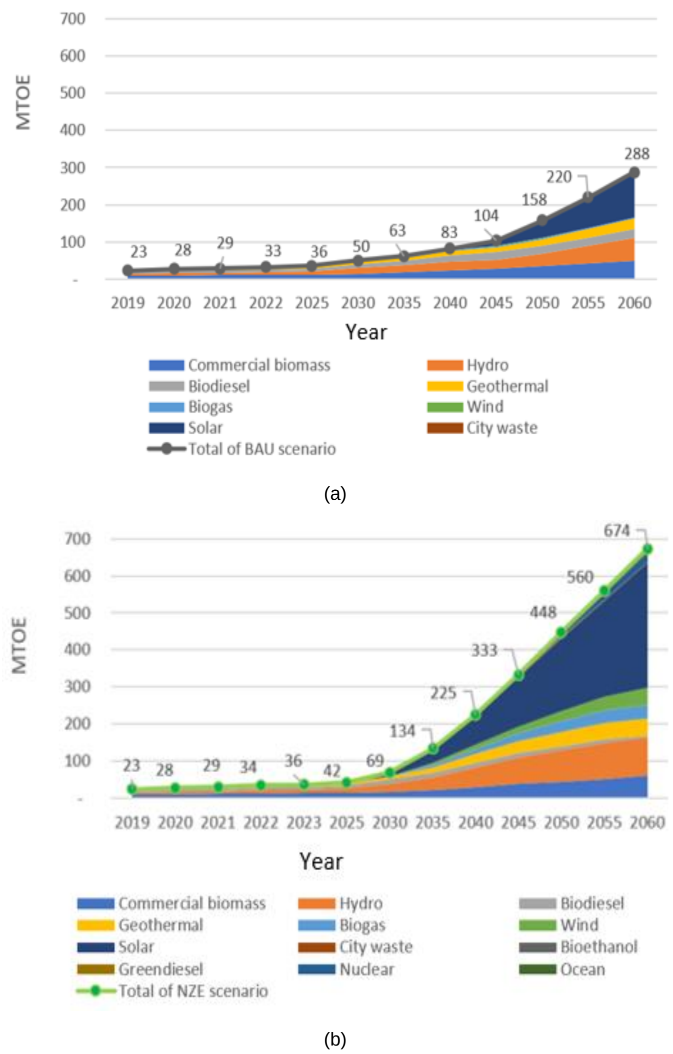

Figure 4. NRE supply in (a) BAU scenario and (b) NZE scenario.

experiences the highest growth rate, averaging 21% per year. It increases from 0.06 MTOE in 2019 to 120 MTOE by 2060. This rise corresponds with the growing contribution of solar power to the total renewable energy mix, which climbs from 0.2% in 2019 to 42% in 2060.

PLTS systems with photovoltaics offer significant technical and economic integration potential, even without relying on battery storage [27]. The second increase was in municipal solid waste power generation, which saw an average annual growth rate of 13%. Although its use was relatively modest—only 0.01 MTOE in 2019—it is projected to rise to 1.1 MTOE by 2060. Meanwhile, biogas grows at an annual rate of 7%, with its share increasing from 0.7% in 2019 to 0.9% by 2060.

Additionally, energy from hydro and wind sources has been growing at an average rate of 6% per year. However, their contributions are projected to decrease from 23% and 0.7% in 2019 to 21% and 0.6% by 2060. Geothermal power generation's share declined from 15% to 10%, but its growth rate increased by 5% per year. Meanwhile, between 2019 and 2060, the shares of biodiesel and biomass decreased from 21% to 8% and from 39% to 18%, respectively. Although geothermal power generation's share fell, its growth rate rose by 5% per year. In contrast, biodiesel and biomass experienced an average growth rate of 4% per year during this period.

The results of the BAU scenario are higher than those found in previous research using the BAU scenario based on the

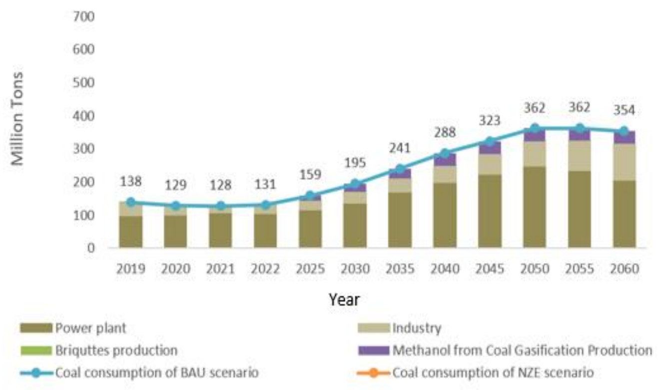

Figure 5. Coal utilization of BAU and NZE scenarios.

2019–2028 PLN Electricity Business Plan, which did not include targets for renewable energy [28]. According to the study, the energy source composition in 2050 is projected to include hydro (2.75%), geothermal (2.86%), biomass (0.07%), solar (0.16%), wind (0.19%), natural gas (28.48%), coal (65.49%), and petroleum (0%).

The NZE scenario for the 2019–2060 period projects an average annual increase of 9% in total NRE supply, rising from 23 MTOE in 2019 to 674 MTOE by 2060 This represents a 2.3-fold increase compared to the BAU scenario. The growth is attributed to energy sources such as waste, wind, biogas, hydro, geothermal, and commercial biomass. Additionally, bioethanol is expected to contribute from 2026 to 2052, while green diesel is projected to be introduced between 2030 and 2060. Nuclear energy and ocean energy sources are anticipated to come online between 2045 and 2060. Nuclear power plants (NPPs) are considered the most viable option for replacing coal-fired power plants in the future [29].

The supply of NRE in both the BAU and NZE scenarios in this study is consistent with findings from similar studies conducted in ASEAN countries [30]. The study indicates that electricity generation from fossil fuels gradually declines to zero by 2050. In contrast, electricity generation from renewable sources increases 16-fold, rising from 247 TWh in 2020 to 3,696 TWh by 2050. By that year, NRE accounts for 99.5% of total electricity generation, with the remaining 0.5% coming from nuclear power. Solar PV dominates the electricity generation mix with a 61% share, followed by wind energy at 17%.

C. RESULTS OF ENERGY UTILIZATION

The results of energy utilization under both the BAU and NZE scenarios include the use of coal, fuel, gas, and NRE.

1) COAL UTILIZATION

By 2060, coal use is projected to reach 354 million tons. However, it falls sharply to 66 million tons in the NZE scenario, marking an 81% reduction. This decrease is driven by the phase-out of coal-fired power plants and a shift toward renewable energy sources, especially solar, hydropower, and wind power.

In addition, coal use in the industrial sector is 108 million tons in the BAU scenario but declines sharply to 28 million tons in the NZE scenario. However, it is important to note that methanol production from coal gasification, starting in 2024, will increase gradually to 38 million tons by 2060. This production grows at an annual rate of 6% in both scenarios, as illustrated in Figure 5.

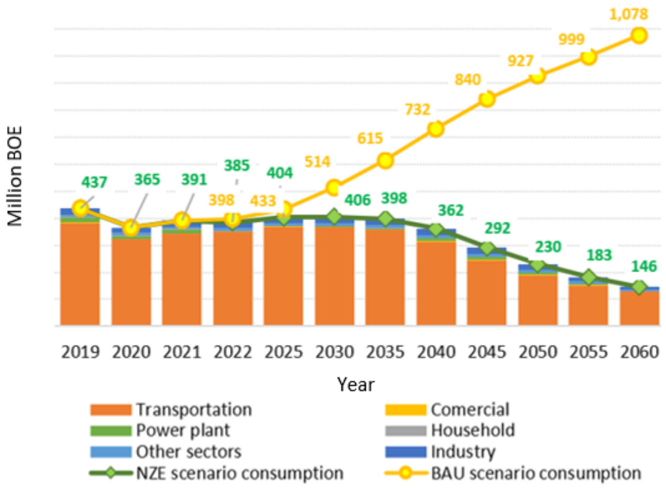

Figure 6. Fuel utilization in BAU and NZE scenarios.

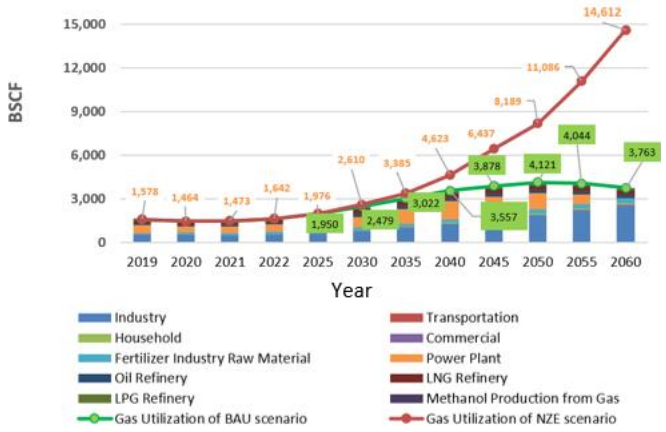

Figure 7. Gas utilization in BAU and NZE scenarios.

2) FUEL UTILIZATION

Figure 6 illustrates fuel utilization in both the BAU and NZE scenarios. The comparison between these scenarios covers the period from 2022 to 2060 and considers the fuel reduction target. It is projected that total fuel utilization will decrease significantly, from 3% in 2022 to 86% by 2060.

The largest reduction in fuel use is expected in the transportation sector, with a decrease of 87% due to the shift from fuel-powered to electric vehicles. Despite this decline, jet fuel and gasoil will still be necessary during the transition period. Additionally, fuel use in the industrial and other sectors is projected to decrease by 40% each by 2060.

By 2060, the commercial and residential sectors are anticipated to cease using fuel entirely, switching completely to electricity. Furthermore, power plants that rely on fuel are expected to be either discontinued or not operational by that time.

3) GAS UTILIZATION

The BAU and NZE scenarios do not impact gas utilization in the fertilizer industry, refineries (including liquefied natural gas/LNG, oil, and liquefied petroleum gas/LPG), or methanol production from 2019 to 2060. By 2060, gas usage in the NZE scenario is projected to decrease significantly, with a complete shutdown in power generation, approximately 40% reduction in the commercial sector, 21% in industry, and 3% in households.

During the energy transition, electricity generation will shift from gas to renewable sources. Additionally, gas use in the transportation sector is projected to rise to 6.2 BSCF by 2060, up from 0.2 BSCF under the BAU scenario, as illustrated in Figure 7.

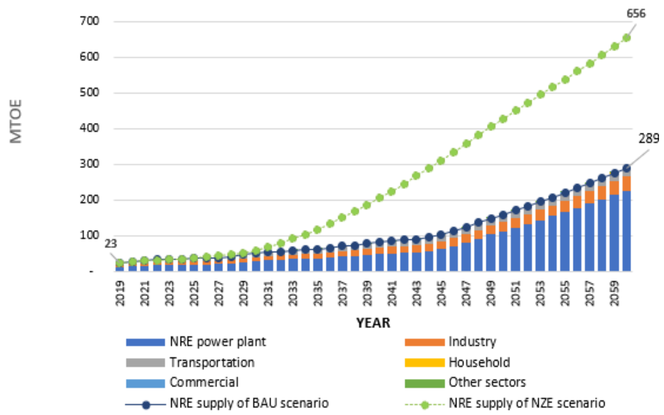

Figure 8. NRE utilization in BAU and NZE scenarios.

4) NRE UTILIZATION

During the period from 2019 to 2060, the goal to gradually reduce and eventually phase out fossil energy use implies that no new fossil fuel power plants will be constructed. Among the renewable energy sectors, the most significant is renewable energy power plants. It is estimated that under the BAU scenario, there will be an average annual increase of 7%, growing from 13 MTOE in 2019 to 266 MTOE in 2060. In contrast, under the NZE scenario, the average annual increase is expected to be 10%, rising from 13 MTOE in 2019 to 607 MTOE in 2060. This means that by 2060, the NZE scenario will result in 2.7 times the amount of renewable energy compared to the BAU scenario.

In addition to its use in power generation, the utilization of NRE in the industrial sector is projected to increase from 6 MTOE in 2019 to 39 MTOE by 2060 under the BAU scenario, and to 30 MTOE by 2060 under the NZE scenario, representing a 24% decrease compared to the BAU scenario.

In addition, the utilization of NRE in the commercial sector is expected to increase from 0.2 MTOE in 2019 to 0.5 MTOE by 2060. In the household sector, NRE utilization is projected to remain constant at 0.1 MTOE from 2026 to 2060. Alternatively, both sectors are expected to see a 40% decrease compared to the BAU scenario. In the transportation sector, NRE utilization is expected to grow from 4 MTOE in 2019 to 22 MTOE by 2060 under the BAU scenario, and to 18 MTOE under the NZE scenario, which is an 18% decrease compared to the BAU scenario, as shown in Figure 8.

IV. CONCLUSION

The G20 conference in Bali urged both developed and developing countries to accelerate their energy transition towards net-zero emissions by 2060, due to the depletion of fossil fuel reserves. Using the LEAP model, the impact of the NZE scenario on energy supply in 2060 is projected to be significant. Coal, petroleum, and gas production are expected to decline by 81%, 87%, and 74%, respectively, while petroleum production will remain unaffected.

The utilization of NRE in the NRE power plant is expected to increase significantly by 2060, with the NZE scenario leading to an approximately 2.7-fold rise compared to the BAU scenario. In the industrial sector, renewable energy utilization is projected to decrease by 24% compared to BAU. Meanwhile, in the commercial and household sectors, NRE usage is anticipated to drop by 40% compared to BAU. In the transportation sector, despite an increase in the BAU scenario, NRE utilization in the NZE scenario is expected to decrease by 18% compared to BAU in 2060.

LEAP has limitations in managing the vast complexity of data and the constantly evolving dynamics of the energy system. Artificial intelligence (AI) presents an alternative for more deeply exploring patterns that may be challenging for LEAP to identify. Future research could employ AI models capable of predicting more dynamic and adaptive energy transformations, as well as identifying innovative solutions for optimizing the future energy mix.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest with any parties or institutions related to the preparation of this paper.

AUTHORS' CONTRIBUTIONS

Conceptualization, Widhiatmaka, and Nona Niode; methodology, Joko Santosa; software, Joko Santosa; validation, Erwin Siregar; formal analysis, Arif Darmawan; investigation, Prima Trie Wijaya; resources, Nona Niode; data curation, Nona Niode; writing-original drafting, Widhiatmaka and Nurry Widya Hesty; writing-reviewing and editing, Agus Nurrohim and Erwin Siregar; visualization, Prima Trie Wijaya and Afri Dwijatmiko; supervision, Arif Darmawan.

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REFERENCES

[1] V.S. Husada and I.E. Joesoef, "Legal policy of the Indonesian government to achieve net zero emissions," *J. Res. Soc. Sci. Econ. Manag.*, vol. 2, no. 1, pp. 128–133, Aug. 2022, doi: 10.59141/jrssem.v2i1.248.

[2] N. Shofiyana, I. Supriyadi, and M.U.A. Qarni, "Transisi energi Indonesia pasca pandemi COVID-19 dan konflik militer Rusia-Ukraina," *J. Kewarganegaraan*, vol. 6, no. 2, pp. 3381–3387, Sep. 2022.

[3] M.Z. Jacobson et al., "100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world," *Joule*, vol. 1, no. 1, pp. 108–121, Sep. 2017, doi: 10.1016/j.joule.2017.07.005.

[4] L. Suganthi and A.A. Samuel, "Energy models for demand forecasting—A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 2, pp. 1223–1240, Feb. 2012, doi: 10.1016/j.rser.2011.08.014.

[5] P. Misila, P. Winyuchakrit, and B. Limmeechokchai, "Thailand's long-term GHG emission reduction in 2050: The achievement of renewable energy and energy efficiency beyond the NDC," *Heliyon*, vol. 6, no. 12, pp. 1–17, Dec. 2020, doi: 10.1016/j.heliyon.2020.e05720.

[6] M. Shahid *et al*., "LEAP simulated economic evaluation of sustainable scenarios to fulfill the regional electricity demand in Pakistan," *Sustain. Energy Technol. Assess.*, vol. 46, pp. 1–13, Aug. 2021, doi: 10.1016/j.seta.2021.101292.

[7] M. Azam *et al*., "Energy consumption and emission projection for the road transport sector in Malaysia: An application of the LEAP model," *Environ. Dev. Sustain*., vol. 18, no. 4, pp. 1027–1047, Aug. 2016, doi: 10.1007/s10668-015-9684-4.

[8] J.D. Correa-Laguna, M. Pelgrims, M.E. Valderrama, and R. Morales, "Colombia's GHG emissions reduction scenario: Complete representation of the energy and non-energy sectors in LEAP," *Energies*, vol. 14, no. 21, pp. 1–24, Nov. 2021, doi: 10.3390/en14217078.

[9] V. Sessa, R. Bhandari, and A. Ba, "Rural electrification pathways: An implementation of LEAP and GIS tools in Mali," *Energies*, vol. 14, no. 11, pp. 1–19, Jun. 2021, doi: 10.3390/en14113338.

[10] D. Yang *et al*., "Critical transformation pathways and socio-environmental benefits of energy substitution using a LEAP scenario modeling," *Renew. Sustain. Energy Rev*., vol. 135, pp. 1–12, Jan. 2021, doi: 10.1016/j.rser.2020.110116.

[11] J.H. Hong *et al*., "Long-term energy strategy scenarios for South Korea: Transition to a sustainable energy system," *Energy Policy*, vol. 127, pp. 425–437, Apr. 2019, doi: 10.1016/j.enpol.2018.11.055.

[12] D.J. Massaga, G. Kirkil, and E. Celebi, "A Comparative study of energy models for Turkish electricity market using LEAP," in *2019 16th Int. Conf. Eur. Energy Mark. (EEM)*, 2019, pp. 1–4, doi: 10.1109/EEM.2019.8916283.

[13] K. Handayani, Y. Krozer, and T. Filatova, "From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning," *Energy Policy*, vol. 127, pp. 134–146, Apr. 2019, doi: 10.1016/j.enpol.2018.11.045.

[14] D.S. Nurwahyudin, N. Trihastuti, and N.A. Utama, "Energy planning in West Java using software LEAP (long-range energy alternatives planning)," in *7th Int. Conf. Energy Environ. Epidemiol. Inf. Syst. (ICENIS 2022)*, 2022, pp. 1–18, doi: 10.1051/e3sconf/202235901001.

[15] L. Sani, D. Khatiwada, F. Harahap, and S. Silveira, "Decarbonization pathways for the power sector in Sumatra, Indonesia," *Renew. Sustain. Energy Rev.*, vol. 150, pp. 1–11, Oct. 2021, doi: 10.1016/j.rser.2021.111507.

[16] "Handbook of Energy & Economic Statistics of Indonesia 2021," Ministry of Energy and Mineral Resources Republic of Indonesia, 2022.

[17] "Proyeksi Penduduk Indonesia 2015-2045 Hasil SUPAS 2015," Statistics Indonesia, 2018.

[18] BPS-Statistics Indonesia, "Berita Resmi Statistik 2023 No. 15/02/Th. XXV, no. 6 Februari 2023," 2023, [Online], https://www.bps.go.id/id/pressrelease/2023/02/06/1997/ekonomi-indonesia-tahun-2022-tumbuh-5-31-persen.html, access date: 1-Mar-2023.

[19] A. Sugiyono, J. Santosa, Adiarso, and E. Hilmawan, "Pemodelan dampak COVID-19 terhadap kebutuhan energi di Indonesia," *J. Sist. Cerdas*, vol. 3, no. 2, pp. 65–73, Aug. 2020, doi: 10.37396/jsc.v3i2.65.

[20] Stockholm Environment Institute, *LEAP: The Low Emissions Analysis Platform.* [Software version: 2020.1.76]. Somerville, MA, USA: Stockholm Environment Institute, 2022.

[21] B. Ugwoke *et al*., "Low emissions analysis platform model for renewable energy: Community-scale case studies in Nigeria," *Sustain. Cities Soc*., vol. 67, Apr. 2021, Art. no. 102750, doi: 10.1016/j.scs.2021.102750.

[22] M. Artzrouni, "Mathematical demography," *Encycl. Soc. Meas*., 2005, pp. 641–651, doi: 10.1016/B0-12-369398-5/00360-1.

[23] R.A. Aprilianto and R.M. Ariefianto, "Peluang dan tantangan menuju net zero emission (NZE) menggunakan variable renewable energy (VRE) pada sistem ketenagalistrikan di Indonesia," *J. Paradigma, J. Multidisipliner Mhs. Pascasarj. Indones*., vol. 2, no. 2, pp. 1–13, Dec. 2021, doi: 10.22146/jpmmpi.v2i2.70198.

[24] M. Triani and K. Dewi, "Carbon emission reduction and indicative carbon revenue in the coal-fired power plants in Indonesia," in *8th Int. Conf. Workshop Basic Appl. Sci. (ICOWOBAS)*, 2021, pp. 1–8, doi: 10.1063/5.0103750.

[25] Bapennas (2023) "Segera bergabung dengan OECD, strategi mewujudkan Indonesia Emas 2045," [Online], https://www.bappenas.go.id/berita/segera-bergabung-dengan-oecd-strategi-mewujudkan-indonesia-emas-2045-9yHr9, access date: 10-Oct-2023.

[26] N.A. Pambudi *et al*., "Renewable energy in Indonesia: Current status, potential, and future development," *Sustainability*, vol. 15, no. 3, pp. 1–29, Feb. 2023, doi: 10.3390/su15032342.

[27] J.A. Ordonez, M. Fritz, and J. Eckstein, "Coal vs. renewables: Least-cost optimization of the Indonesian power sector," *Energy Sustain. Dev*., vol. 68, pp. 350–363, Jun. 2022, doi: 10.1016/j.esd.2022.04.017.

[28] S.P. Kanugrahan, D.F. Hakam, and H. Nugraha, "Techno-economic analysis of Indonesia power generation expansion to achieve economic sustainability and net zero carbon 2050," *Sustainability*, vol. 14, no. 15, pp. 1–25, Aug. 2022, doi: 10.3390/su14159038.

[29] I. Utami, M.A. Riski, and D.R. Hartanto, "Nuclear power plants technology to realize net zero emission 2060," *Int. J. Bus. Manag. Technol*., vol. 6, no. 1, pp. 158–162, Jan./Feb.2022.

[30] K. Handayani *et al*., "Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050," *Appl. Energy*, vol. 311, pp. 1–19, Apr. 2022, doi: 10.1016/j.apenergy.2022.118580.