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The Optimization of Power Generation Mix to Achieve Net Zero Emission Pathway in Indonesia without Specific Time Target

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ABSTRACT

Indonesia is committed to achieving Net Zero Emission (NZE) conditions by the year 2060, with policy adjustments and constraints being necessary to realize this goal. The aim of this study is to achieve NZE conditions using a least-cost optimization method for various power plants that rely on fossil and non- renewable energy sources, without specifying a target year. Two scenarios, Business as Usual (BAU) and NZE, were developed for comparison in the optimization analysis. Through the utilization of LEAP and NEMO software, the optimization results suggest that optimal NZE conditions in Indonesia could be attained by 2075, with solar-based electricity generation playing a crucial role in meeting basic electricity demands. The NZE scenario predicts a 28% rise in electricity demand by 2100 compared to the BAU scenario. In 2075, PV will contribute 32.8% (224.3 GW) to total power supply, while BESS will provide 198.8 GW according to the NZE scenario. This study aims to assist the Indonesian government and stakeholders in reaching the NZE goal, while maintaining current efforts to avoid new efficiency and financial challenges. Achieving this goal will involve using a cost-effective optimization approach and implementing energy-efficient technologies and conservation programs.

Keywords

New and Renewable Energy;
Net Zero Emission;
Power Generation;
Optimization

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1. Introduction

The primary objective of Paris Agreement is limiting the escalation of global temperatures to 1.5 °C above pre-industrial levels by the end of the century [1]. To accomplish this objective, various nations, including Indonesia, have committed to reach their Net Zero Emission (NZE) targets. In 2010, Indonesia established an initial Nationally Determined Contribution (NDC) target, subsequently refining it into an Intended NDC in 2015, thereby augmenting the Greenhouse Gas (GHG) reduction objective to 29% by 2030 (unconditional) and 41% (conditional) relative to Business As Usual (BAU) conditions in 2030 [2]. Energy sector is responsible for around 70% of global GHG emissions, and Indonesia is currently the largest GHG emitter in Southeast Asia [3]. The adoption of New and Renewable Energy (NRE)-based technologies across all facets of energy landscape

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Abbreviations

BAU	Business As Usual
CCS	Carbon Capture Storage
CSPP	Coal Steam Power Plant
CPO	Crude Palm Oil
COP	Conference of the Party
EU	European Union
GCC PP	Gas Combined Cycle Power Plant
GHG	Green House Gas
GJ	Gigajoule
FOLU	Forestry and Land Use
IEA	International Energy Agency
IPPU	Industry Process and Product Use
LTS–LCCR	Long-Term Strategy–Low Carbon Climate Resilience
LEAP	Low Emissions Analysis Platform
LP	Linear Programming
MEMR	Ministry of Energy Resources and Mineral
NDC	Nationally Determined Condition
NRE	New and Renewable Energy
NZE	Net Zero Emission
NEMO	Next Energy Modelling System Optimization
PP	Power Plant
PT PLN	National Electricity Company
PGT	Power Generation Technology
RUPTL	Indonesia Electricity Power Supply Business Plan
USD	United State Dollar

emerges as a plausible resolution. Recognizing that power generation technology is the foremost consumer of fossil fuels, imperative measures involve the replacement of coal- centric power generation in Indonesia. According to the Indonesia Electricity Power Supply Business Plan (RUPTL) [4], current utilization of coal in Indonesian power plants constitutes 52% of overall power plants, whereas gas utilization stands at a mere 29%.

Many parties have interpreted the goal of achieving NZE in Indonesia, with some setting an ambitious target of 2050 [5]. Indonesia, at COP-26, planned to achieve NZE by 2060 in collaboration with IEA and MEMR [6]. Setting a sooner target year will bring policy constraints and economic losses due to early phase-out of fossil-based power plants. Currently, there are no regulations governing the NZE target year in Indonesia. The Indonesian government is currently working on a plan to achieve carbon neutrality by 2060 or earlier. Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) is one of the programs that has been implemented to balance economic growth with reducing emissions and addressing climate-resilient development, equity, and emission reductions [7]. To achieve the NZE target, coal-based power plants will need to be suspended. Yet, this may result in losses for state in terms of power plant manufacturing investment, as the newest Coal Steam Power Plant (CSPP) still has a life span of 250 to 30years.

According to studies in Europe, PV power plants are a type of NRE-based power plant that can help reduce GHG emissions. The European Union (EU) plans to implement Photovoltaic (PV) and reduce GHGemissions by 55% by 2030 [8] Based on this study, PV is considered the main NRE generator in Indonesia to replace CSPP, which is currently the dominant source of base load energy. In Indonesia, photovoltaic (PV) technology has been recognized for an extensive duration, and presently, it has also integrated RooftopPV systems in several areas, particularly for clients with electricity consumption ranging from 1,300 VA to 6,600 VA [9], with competitive Levelized Cost of Electricity (LCOE) [10]. France and Sweden are currently using nuclear power plants to meet their electricity baseload needs and plan to achieve NZE targets in 2045 and 2050, respectively [11]. Nonetheless, these countries face several challenges to achieve carbon-neutral conditions. Achieving NZE is an important effort that requires a synergy between energy mix utilization, economy of scale, and technology choices, which presents challenges in the energy infrastructure planning and design process [12]. Therefore, complexity reduction techniques must be used, ranging from straightforward linearization to complicated multi-level approaches that incorporate aggregation and decomposition techniques [13].

To achieve the NZE target, an energy modeling analysis is needed to assist decision-makers plan strategies. This includes tackling three challenges: finding new mitigation options, selecting the right model, and using it for policy analysis [14]. The novelty of this study is to research ways of achieving NZE target without specific target time, while maintaining previously established programs to avoid further issues, particularly in terms of efficiency and economics. In previous research, the achievement of Net ZeroEmissions (NZE) was often tied to a specific target year, such as Handayani and co-authors [3], Breyer and co-authors [5], IEA [6], Santosa and co-authors [15], Rivera and co-authors [16], and Reyseliyani and co-authors [17] significantly influencing the trajectory of technological advancement. One action taken was tophase out a Coal Steam Power Plant (CSPP) used for base load power generation, typically lasting 40 years[18]. This study promotes technological development aligned with the NZE objective. The research will use a cost optimization method and implement energy efficiency and conservation programs.

2. The Past Condition of Indonesia Energy System

This section elucidates the historical data pertaining to the GDP and population growth in Indonesia, alongside the data concerning GHG emission. To derive projections for power generation, it is imperative to consider the existing data on power plants and the short-term planning of the national utility in Indonesia.

2.1. Past evolution of macroeconomic and emission indicator

Over the years, Indonesia has experienced substantial economic progress. While population of the nation fell by roughly 1.01% each year between 1990 and 2019 (see Table 1), Gross Domestic Product (GDP) expanded by an average of 8.4% per year during that period. This growth rate was determined from 1990 to 2019 while accounting for the effects of Covid-19, which led GDP growth rate to fall to –2.1% in 2020. Indonesia, a developing nation, experienced notable rise in individual energy consumption from 2000 to 2010, slightly decreasing in 2020. The economy's size and structure greatly influence the type and amount of energy utilized. [19]. Nation relies on fossil fuels, GHG emissions from energy sector continue to increase at a pace of 4.59% annually [20]. Energy conservation and the adoption of efficient technology are essential because energy sector is the largest global emitter of GHGs [13,14]. The past circumstances will be used to predict future energy consumption and greenhouse gas emissions. This will assist in identifying the best neutral or NZE emission conditions for Indonesia [21–24].

Table 1: Data of economic and emission indicators in indonesia (1990–2020) [13,15,16,17].

Indicator	1990	2000	2010	2019
Population [*million people*]	179.4	206.3	237.6	267.1
Population Growth [%]	1.5	1.4	1.3	1.1
GDP [*billion USD*]	106.1	165	755.1	1,217.8
GDP Growth [%]	7.2	4.9	6.2	5.0
GDP/capita [*USD/capita*]	591.5	799.9	3,177.5	4,559.2
Final Energy Consumption per Capita [*GJ per capita*]	13.6	22.4	27.1	22.4
Energy per Capita [*GJ per capita*]	22.5	28.8	29.6	36.2
National GHG Emission [*ton* CO_2e]	665.9	1,186.2	809.9	1,866.6
Total GHG Emission per Capita [*kg* CO_2e *per capita*]	6.76	5.63	4.68	7.24
GHG Emission from energy sector [*ton* CO_2e]	176.9	317.6	453.2	638.8

2.2. Overview of power generation in Indonesia

The current state of electricity in Indonesia can be seen in Electricity Supply Business Plan (RUPTL) released by the National Utility Company (PT PLN Persero). Recently, an updated version of RUPTL hasbeen issued for years 2021–2030, which shows an increase in the use of new and renewable energy sources.According to the 2021–2030 RUPTL report, capacity of coal-based power plants will increase by approximately 13.8 GW, while gas-based power plants will increase by 5.8 GW. On the other hand, power plants based on NRE, which include hydro, geothermal, solar, wind, and others, will increase by around 21GW, accounting for 51.7% of total accumulated capacity. RUPTL outlines a plan for additional generating capacity to be accumulated over 10 years, as shown in Figure 1.

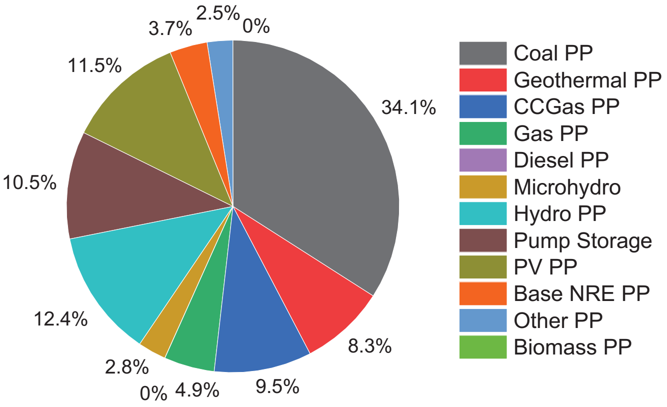

Figure 1: Accumulated power generation capacity addition in ruptl from 2021–2030.

Previous RUPTL report from 2019–2028 had a larger additional capacity of around 56.4 GW, but the increase in NRE capacity was only 29.6% [25]. These figures indicate that the national utility has a plan to achieve carbon-neutral target set by Indonesian government. Establishing a balance between system readiness, economics, and domestic capacity for NRE-based technology production is essential to achieving this goal. PT PLN will gradually retire several Diesel Power Plant units as part of its aim to reach NZE objective in Indonesia and conduct a de-dieselization program to turn them into NRE-based generators [26].

3. Modeling Framework

Modeling framework encompasses a depiction of the software and equations used in the computations. Envisioning the energy system also necessitates assumptions utilized as macroeconomic input, as well as parameters employed as input in the database, specifically for power plant data that will be optimized. Apart from that, it is also imperative to formulate scenarios that can be employed to compare present conditions with the alterations that will be implemented. Subsequently, the conceptual framework of the research conducted will be elucidated.

3.1. LEAP model and data

Analysis of an energy system presents energy modeler with a dense complexity to optimize, particularly when adding new renewable energy into the system. [27]. The Stockholm Environment Institute's LEAP software, which has become popular for integrated energy analysis and assessment of climate change mitigation, was utilized in this study to carry out optimization [28]. There are a considerable amount of research dedicated to achieving the optimization of energy systems through the utilization of LEAP software, there are Sani et al. [29], Adiprasetya et al. [30], Handayani et al. [31], Karunanithi et al. [32], El-sayed [33], Santosa et al. [15], and Rivera-gons et al. [16], and Ren et al. [34].The Low Emission Analysis Platform (LEAP) software optimizes power generation mix to satisfy energy needs using the Next Energy Modelling System Optimization (NEMO) Optimizer [35]. The demand-driven method is utilized by LEAP and some energy system projection software [36], where the amount of final electricity demand defines quantity of capacity and electricity production to be generated as well as kind of power plant to be employed. The amount of electrical demand that will be generated must therefore be projected, and this amount is decided by projection of energy demand in industrial, transportation, home, and commercial sectors. The usage of electricity is now just 15% and 0.1% of the ultimate energy requirements for industrial and transportation sectors, respectively [37]. Since most of equipment used in residential and commercial sectors is powered by electricity, the need for energy has a considerable impact on both of these sectors. The amount of electricity needed in each user sector depends on how technology is used. Though it is predicted that power consumption would increase as quickly as economic growth, the increase in energy users won't necessarily translate into a linear increase in power consumption in the future due to high- efficiency technology [38].

Government of Indonesia (GoI) has promoted the execution of an energy conservation program in energy user sector since 2009, where there is a planned and more effective use of technological equipment[39]. The amount of electricity or energy consumed by end-user is strongly affected by consumer behavior, and energy intensity indicates the amount of energy used per unit of output or activity. The Energy demand-including electricity demand - for energy sector is calculated with following equations [15]:

$$\sum\nolimits_{y} E_{ic} = \sum\nolimits_{ty} A_{ic} \times I \tag{1}$$

$$\sum\nolimits_{y} E_{h} = \sum\nolimits_{y} A_{h} \times \frac{U}{E_{eff}} \tag{2}$$

$$\sum\nolimits_{y} E_{t} = \sum\nolimits_{y} S_{y} \times \frac{D}{C} \tag{3}$$

Where E_{ic} is energy demand for industries and commercial sectors in year y, A_{ic} is activity level for industries and commercial sectors, E_h is energy demand for household sector, A_h is activity level for household sector, E_t is energy demand for transportation sector, S_y is number of vehicles in year y, I is final energy intensity of industries and commercial sectors, U is useful energy intensity for household sectors, E_{eff} is appliance technology efficiency, D is vehicle mileage, and C is specific energy consumption. Then, in transportation sector, a logistics function-modeled equation is used to compute vehicle sales.

$$S_y = S_{y-1} \times (1 + r_y) \tag{4}$$

Where S_{y-1} is number of vehicles in year t–1, and r_y is growth of vehicle sales. Vehicle cycle profiles are used to understand age distributions and technological behavior of different annual ages in-stock autos. Different fuel types development depends on how each user sector adopts technology. LEAP software uses projections for economy, demographics, and regulations as input. Energy demand projections, especially for electricity, help determine fuel mix for power generation using lowest cost approach. Power plant fuel mix in NZE scenario affects GHG emissions and Indonesia's carbon neutral status.

Power plants are optimized using the least-cost optimization method to meet electricity demand. [17]. Using the concepts of linear programming (LP) and/or mixed integer programming (MIP), optimization is carried out to create energy systems that can accommodate electricity demands based on the least cost principle (Equation 5) [15] . Its objective purpose is to obtain the lowest energy system cost to achieve NZE conditions. Variables such as capital cost, fixed cost, capacity, and variable cost of power production technology is considered in the software. The inputs provided to LEAP and results of final optimization are used to determine the optimal time for Indonesia to reach NZE conditions with 2100 as the restriction [40].

$$\begin{aligned} &\min \ \textit{Total Discounted Cost} \\ &= min\left\{\sum\nolimits_r \sum\nolimits_y \frac{1}{(1+d)^{y-yb}} \sum\nolimits_{PGT}\Big[annualized\ capital\ csots\ s_{y,r}\right. \\ &\quad + fixed\cos t\ s_y \times capacity_{PGT,y,r} + operational\cos ts_y \\ &\quad \left.\times \sum\nolimits_t generation_{PGT,y,r}\Big]\right\} \end{aligned} \tag{5}$$

The total discounted cost is calculated by adding fixed costs for each installed capacity of Power Generation Technology (PGT) to total minimum capital cost in a year added by multiplying operational costs by accumulated power plant production, where y is year, y_b is base year, r is a region, d is discount rate, and t is time step. Additionally, TIER 1 provisions of following equation are applied to each fuel type to calculate CO_2 emissions in the LEAP software in compliance with IPCC regulations [16]:

$$PE(y) = \sum\nolimits_p \left[EC_{p,j}(y) * EF_j(y)\right] \tag{6}$$

Where $PE(y)$ is emission from power generation, $EC_{p,j}$ is fuel consumption for generator p and fuel j, while EF_j is emission factor for fuel j in year y. In NZE scenario, total GHG emissions are gradually declined each year until they reach NZE.

3.2 Model Assumption and Parameter

Indonesia's economic development is nonetheless moving quite quickly, even though it is still regarded as a developing nation. The Indonesian economy has become entangled in the Middle-Income Trap, even though the World Bank claims that the nation has begun to transition toward development [41]. Economy of Indonesia is still expected to grow rapidly, despite the World Bank's remark. In line with Bappenas' predictions, Indonesia's GDP is projected to grow at a rate of about 4.06% annually until year 2100 [42,43].

The energy system of Indonesia is assumed as a single region in this model, with a time frame of 2019 to 2100. The base year selected is 2019, as 2020 will be a typical year due to the Covid-19 pandemic, making it challenging to estimate energy needs in that year. The load curve in year 2015 for Java-Bali (Jamali) region is taken into account in this model [15]; it is an updated PLN data that is still accessible. Following that, time and season, specifically wet, dry, day, and night, are computed from load curve, and then divided into 96 time slices. The worldwide potential emission numbers, reserve margins, and macroeconomic projection data entered into LEAP software as assumptions and constraints are displayed in Table 2.

This model takes into account 20 different types of power plants, including pump storage and battery energy storage systems. Table 3 displays the technological requirements for power generation based on electricity, NRE, and storage systems.

Fossil energy-based power plants are being phased out, leading to a need for optimized NRE-based power plants with high efficiency and low costs. These new power plants will replace coal power plants as the main source to meet electricity baseload [49]. Renewable energy output is intermittent, requiring energy storage facilities like pumped storage and battery storage to be

Table 2: Assumptions and constraints of leap model.

Parameter	Value	References
Population Growth	0.4%	[44]
GDP Growth	4.1%	[43]
Reserve Margin [45]	30.0%	[4]
Interest Rate	10.0%	
Global Potential for CH_4 to CO_2e	28	[46]
Global Potential for N_2O to CO_2e	265	[46]
Achieve 1% Energy Intensity reduction per annum till 2025		[34,36]

Table 3: Parameter for modeling power plant.

Technology	**Net Capacity2021 (GW) [4]**	**Lifetime (years) [47]**	**Efficiency (%) [47]**	**Capacity Factor (%) [36,37]**	**Capital Cost (USD/kW) [47]**			
					2021	**2050**	**2075**	**2100**
Coal Steam PP	33.09	40	30–33	68–75	1400	1200	1150	1050
CCS Coal Steam PP**	0	40	35	85	2800	2100	1800	1500
Gas Combined Cycle PP	12.41	40	44	68–73	750	700	700	700
CCS Gas Combined Cycle PP**	0	40	46	75	1600	1500	1250	1000
Gas Steam Power Plant	5.08	30	30	55	1400	1450	1450	1500
Gas Engine PP	2.69	30	40	60	750	700	700	700
Oil Steam Power Plant	0	40	30	20–30	1400	1400	1450	1500
Diesel PP	4.20	25	39	30	800	780	765	750
Hydro PP	5.66	60	30	40–70*	2000	2000	1950	1900
Mini_Microhydro PP	0.48	30	30	40–70*	2600	2600	2550	2500
Pumped Storage	0	60	30	40–70*	750	750	725	700
Geothermal PP	2.53	30	30	80–85	3200	2900	2800	2700
Biomass PP	0	25	25–28	60–70	1600	1500	1450	1400
Biogas PP	0	25	35	60–70	2000	1800	1700	1600
Waste PP	0	25	25–28	30–60	2300	2000	1900	1800
CPO PP	0	25	40	35–50	800	780	765	750
Photovoltaic PP	0.15	25	18–32	Yearly Shape (PV)	1200	800	650	500
Wind PP	0	25	28–30	35–40	1600	1300	1250	1200
Ocean PP	0	30	25	30–35	5000	2200	2000	1800
Nuclear PP	0	40	33	85	6000	5500	4750	4000
Battery Energy Storage (BESS)	0	10	85	90	1400	942.9	871.4	800

*depends on seasons; **Start in 2050

prevalent in power generation [50]. Renewable energy sources are variable and intermittent due to their reliance on weather and climate [51]. Battery Energy Storage Systems are essential for balancing the intermittent energy generated by NRE-based generators [52]. Pump Storage also assists in supporting BESS to function effectively.

3.2. Scenario development

BAU scenario and NZE scenario are two scenarios that are employed in the model. Traditional or fuel wood biomass and commercial biomass are two different ways that biomass is used in this study. Figure 2 depicts the conceptual foundation for this investigation. Industry, transportation, housing, commerce, and other sectors (mining, construction, and agriculture) are five energy-consuming sectors that have projected energy demands based on macroeconomic and population estimates. Additionally, predictable amount of energy supply will be determined by energy demand. The fuel utilized for power generation and energy demand are two main factors in the planning of primary energy supply. The conceptual framework of the research is shown in Figure 2. The scenario's specifics are as follows:

1. **BAU Scenario:** This is the most fundamental scenario, which projects future energy demand if current growth trend holds.
2. **NZE Scenario:** The presumptions involve wide adoption of energy-saving and green technologies, NRE demand and supply for achieving Net Zero Emission in power production. This includes gradually phasing out CSPP and other fossil generators, accelerating development of NRE generators like PV, Wind, biomass, and nuclear powerplants, maximizing NRE potential,

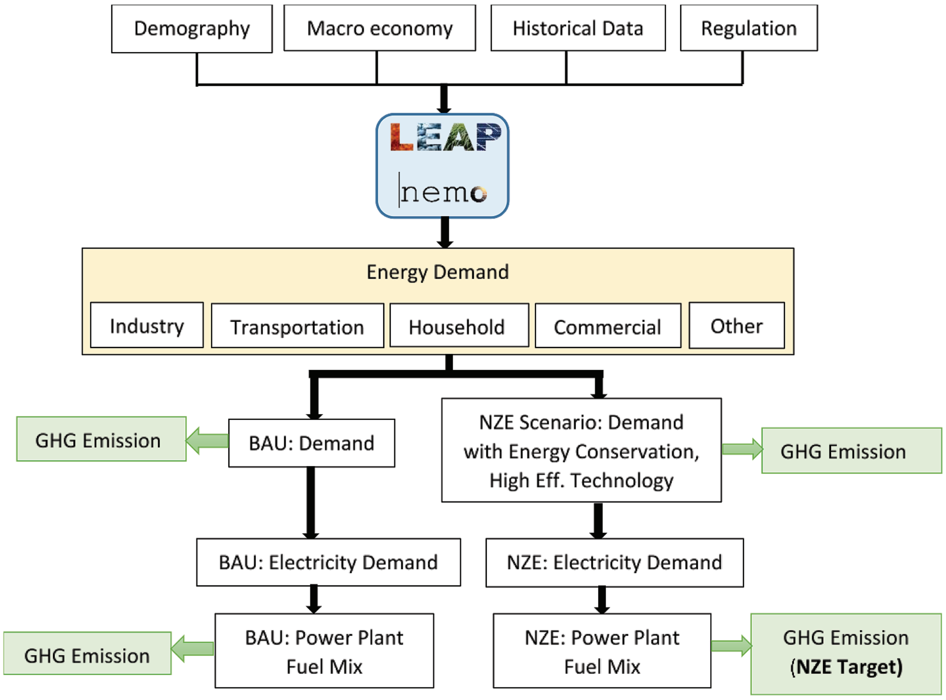

Figure 2: Conceptual framework of the research.

utilizing battery-powered vehicles, enhancing electricity distribution system, and applying energy-saving technology to end-use demand. Additionally, carbon capture technology, development of biofuel infrastructure, green hydrogen are crucial for reducing GHG emissions in the industrial sector.

This study examines the inclusion of CCUS and CCS in power generation, delayed by cost and land constraints [53]. Not all sedimentary basins are suitable for CO_2 storage, needing specific characteristics. A basin considered for carbon storage needs specific characteristics, including a dense concentration of basins, permeable rock formations saturated with saltwater, a layer of rock with low porosity, and a geologically straightforward structure [54]. Examining CCS technology deployment in Indonesian power plants is crucial due to land competition. LCOE for CCS technology in power plants can increase significantly compared to CSPP. However, from the learning curve, the cost of CCS CSPP will decrease over time, aligning with NRE power plants [55,56]. Net-zero emissions require synergy between Emission Trading Scheme and CCS [57]. CCS technology is projected to be effective from 2050 in this study. A prior study in Thailand also did not include CCS technology until 2050 [58].

Figure 2 describes the conceptual framework employed in this study's research. Input for calculations in the Low Emission Analysis Platform (LEAP) model comprises demographic data, macroeconomics, historical data, and relevant regulations. These data are utilized for projecting energy demand from all energy sector, such as industry, transportation, household, commercial, and other (ACM) sector, which comprise of agriculture, construction and mining activities, as a demand driven. Moreover, techno- economic data is included, focusing on technology efficiency in the energy and power generation field. Utilizing the NEMO optimizer, the research produces optimized outcomes for electricity generation mix to meet energy needs at minimal expense. Subsequently, emissions from the fuel are computed to achieve Net Zero Emission in the NZE scenario.

4. Result and Discussion

The section will discuss outcomes of optimization in relation to energy requirements across all sectors.Power generation optimization is driven by electricity demand. It will explain the mix of electricity generation capacity and resulting production to meet demand. Net Zero Energy (NZE) achievement will be described, including supply of electrical energy throughout the year. NZE attainment will be discussed in terms of emissions reduction by 2075. Comparison will be made between emission reductions from energy demand and electricity generation. The discussion will also cover investment and production costs for the power plant under different scenarios.

4.1. Electricity demand projection

The NZE scenario considers high-efficiency technology and energy conservation in technology applications, energy demand in BAU scenario relies on current technology with slight adjustments. Electricity is crucial for production in developing countries such as Indonesia. The Indonesian power sector is facing challenges due to increasing electricity demand from population growth, economic development, and improved energy access [29]. Electricity-based technology is widely utilized across energy-consuming sectors, leading to an increase in electricity demand in a Net Zero Energy (NZE) scenario. Industrial sector considers high-efficiency boiler, furnace, and electricity-based applications during energy transitions. In transportation sector, energy conversion and conservation are implemented by switching out gasoline- powered vehicles for hybrid and electric vehicles [59]. In residential sector, more energy-efficient lighting is used, and LPG stoves are progressively replaced by induction cooktops with an efficiency of more than 85% [47]. This is done because the majority of Indonesia's LPG needs are currently satisfied by imports. Therefore, in NZE scenario total energy demand will increase less than expected, while the need for electrical energy will continue to grow.

By introducing high-efficiency appliances across all user sectors in NZE scenario, the total final energy demand will drop by about 27.6% of what it would have been in 2100 under BAU scenario. Nevertheless, the increased use of electricity-based technologies, has resulted in a 28% increase in the electricity demand in NZE scenario compared to BAU scenario (Figure 3). In BAU scenario, electricity demand will rise to 4,037 TWh in 2100, or approximately 11,152 kWh per capita, whereas it will be 4,649 TWh, or 12,844 kWh per capita, in NZE scenario.

4.2. Electricity generation mix

In BAU scenario, number of Coal Steam PP and gas power plants (GasPP), particularly combined cycle gas power plants (GCC PP), keeps rising. By introducing CCS CSPP and CCS GCCPP in this scenario, the overall rise in generating capacity amounts to 3.6%. Along with Photovoltaic Power Plant (PVPP), hydro power plant (Hydro PP) and geothermal power plant (Geothermal PP) will also contribute to nation's electricity output. A new nuclear plant will subsequently follow, with a capacity of 3.0 GW in 2092 and a growth to 30 GW in 2100. BESS is required to overcome the NRE generator's interruption due to PVPP's dominance. BESS has a 3.5 GW capacity in 2048 and a 200 GW capacity in 2100. While other fossil-based power plants like GCC-PP, Gas Power Plant (Gas PP), and Diesel PP continue to lose capacity and reach zero in 2075 under NZE scenario, PVPP capacity has sharply increased with a growth rate of 9.1% per year, reaching 224.3 GW in 2075, followed by Wind PP at 118 GW, and complemented by BESS at 199 GW (Figure 4). Total growth of power capacity in NZE scenario is 4% per year.

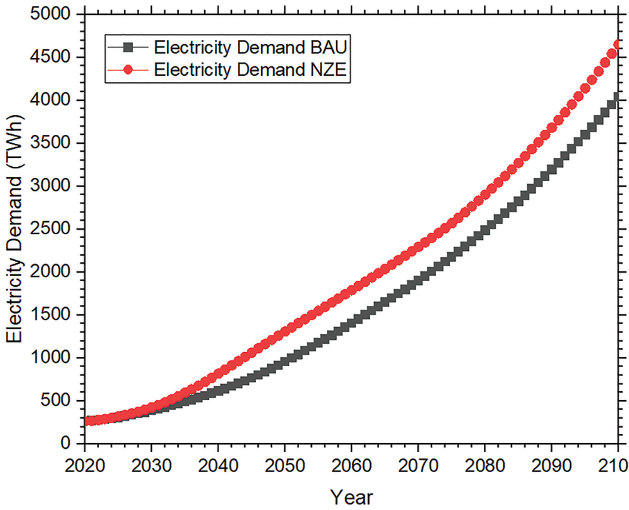

Figure 3: Projection of electricity demand for bau and nze scenario.

Under BAU scenario, coal will account for 67.2 70.2% of all electricity produced in the country in 2020 (Figure 5). Despite this, the use of coal plants will continue to decline until 2050 due to the introduction of green electricity in RUPTL 2021–2030. At that point, the amount of electricity produced by CSPP will be 31.2%, and it will continue to decline until it reaches 10.4% in 2100. Production from power plants in GCC PP will rise to 17.9% in 2050 before falling to 7.1% in 2100. CCS CSPP and CCS GCC PP commenced to generate electricity respectively in the year 2081 and 2076. In BAU scenario, energy output from PVPP increases quickly to 5.8% in 2050 and becomes dominant by 28.2% in 2100 as a result of changes in PV generation costs. Particularly in NZE scenario, gas and coal steam

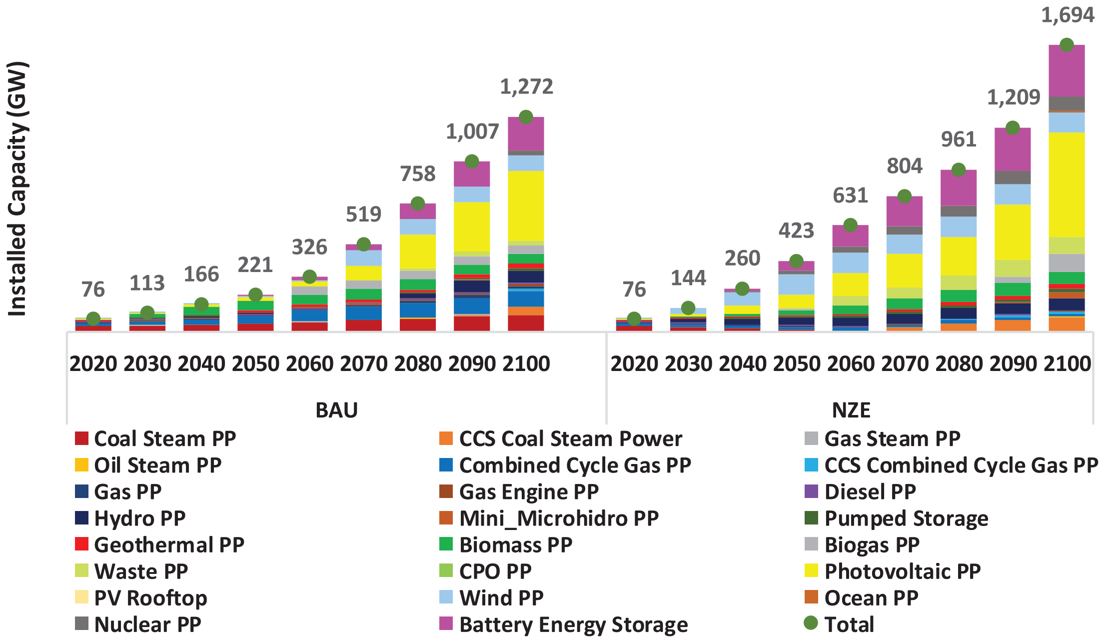

Figure 4: Comparison of installed capacity of bau and nze scenario.

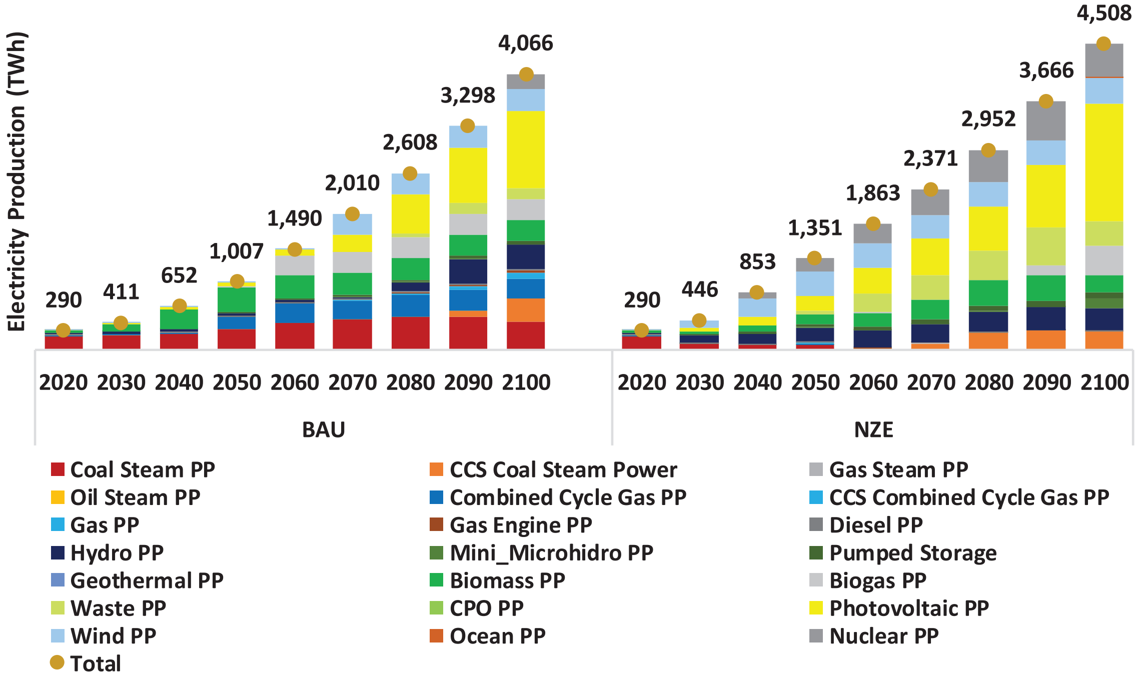

Figure 5: Comparison of electricity production of bau and nze scenario.

power plants experience significant declines that eventually reach zero in 2075, indicating that power sector has reached NZE conditions. The quantity of photovoltaic (PV) electricity generated has experienced a significant rise during this period, reaching 1,742.5 TWh in 2100 under NZE scenario, compared to 1,147.4 TWh under BAU scenario, constituting 38.7% of the overall national energy production. CPO and ocean current-based power plants are not currently competitive because of their high initial investment costs.

Allowing to the optimization results, both the BAU and NZE scenarios in 2100 will primarily use solar-based photovoltaic power plants. In the NZE scenario by 2075, oil, gas, and coal power plants will no longer be competitors. Figure 6 shows the NZE scenario for power generation in 2075, with various types of power plants filling base and peak loads to support Indonesia achieve NZE conditions. Battery Energy System Storage will help fill medium and peak loads when solar and wind power are not available [52]. Oil, coal, and gas power plants will no longer be used, except for CCS for CSPP and CCG PP which consider as NRE based power plant. The negative value on the graph shows BESS getting energy from PVPP between hour10 and 15 on weekdays in rainy and dry seasons. BESS replenishes energy from PVPP during the day and grid-level batteries store excess energy from wind and solar for peak demand [60].

PVPP will predominate in fulfillment of the electricity supply and fill energy in BESS during the wet and dry seasons, during the day on both weekdays and weekends. Following that, the base and medium loads will be satisfied by Biomass PP, Geothermal PP, and Hydro PP, while PVPP, Wind PP and BESS will take care of the peak loads. This yearly pattern of Power Generation behavior is expected to continue until 2100, when PV and biomass power generation will perform a more significant part.

4.3. GHG emission reduction

4.3.1 Achieving NZE target

The results of the power plant emissions under NZE scenario are shown in Figure 7. According to the outcomes of optimizing mixture of power plants used in NZE scenario, by introducing CCS power plant in 2050, the goal of NZE or zero emissions in the energy mix of power plants will be achieved in 2075, or nearly 15 years after the government's previously stated NZE target estimations. This demonstrates that by taking into account generation costs, efficiency, and longevity from a generator without a policy limitation, the NZE will be accomplished in a longer amount of time.

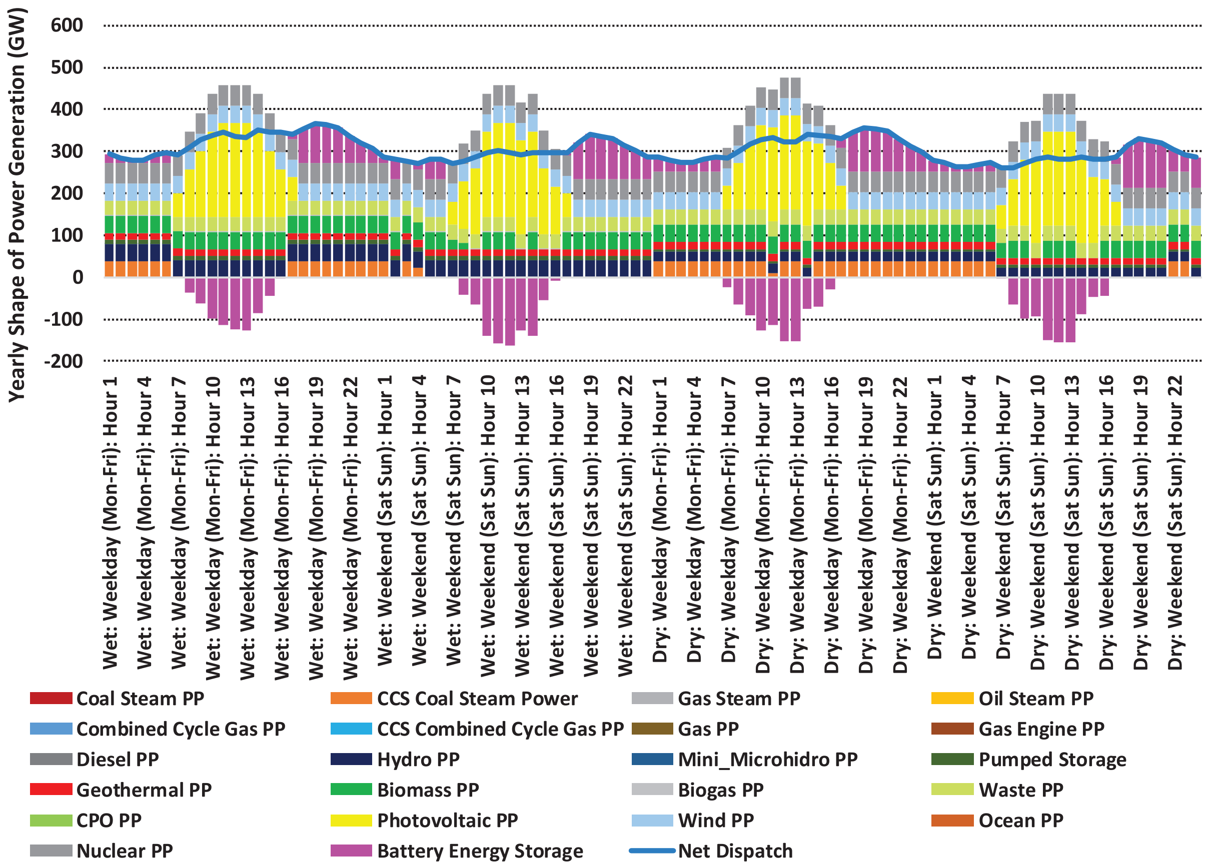

Figure 6: Yearly shape of power generation in 2075 (nze scenario).

4.3.2 GHG Emission Reduction

In NZE scenario, energy conservation results in a reduction of emissions in both energy consumption and power generation sectors. Figure 8 displays a comparison of emissions from power plants for the two possibilities. The NDC target for Indonesia is based on the Updated Nationally Determined Contribution Republic of Indonesia 2021 [2], which states that Indonesia will reduce emissions in the energy sector by 314 Mt of CO_2 equivalent in 2030. However, according to the study, this reduction in emissions occurred in the same year and was 66 Mt of CO_2 equivalent, which is less than the NDC target in 2030. Only in 2042will there be a start to emission reductions of more than 314 Mt of CO_2 equivalent. The difference between the reductions in power plant emissions and the variation in energy demand will start to exceed each otherin 2075, and this situation will persist until 2100.

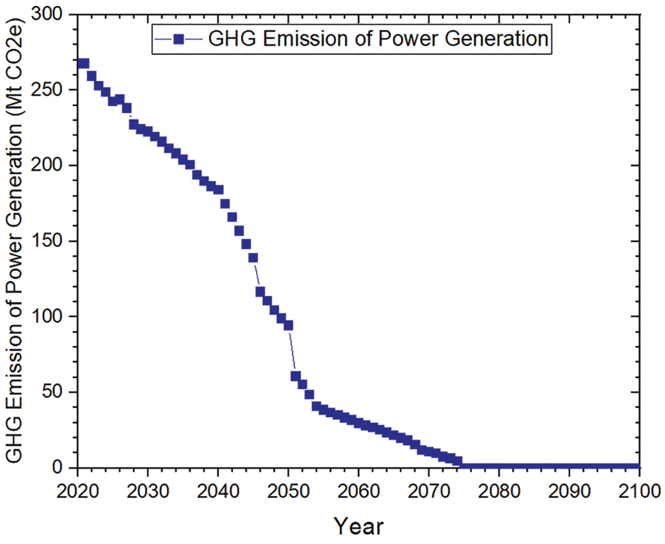

Figure 7: NZE target is achieved in 2075 for ghg emission of power generation mix in nze scenario.

4.4. Cost of power generation

The NZE scenario incurs a higher investment cost compared to BAU scenario due to using New and Renewable Energy power plants, leading to a 32.3% increase in total investment from 2020 to 2100. LCOE for NRE plants is higher than fossil-based plants, causing the disparity in investment cost. Productioncosts in BAU and NZE scenarios are gradually decreasing by 6.12% and 6.05% respectively to promote competitiveness of NRE-powered plants and reduce emissions. The drop-in production costs in BAU scenario is anticipated to accelerate the achievement of emission reduction condition because

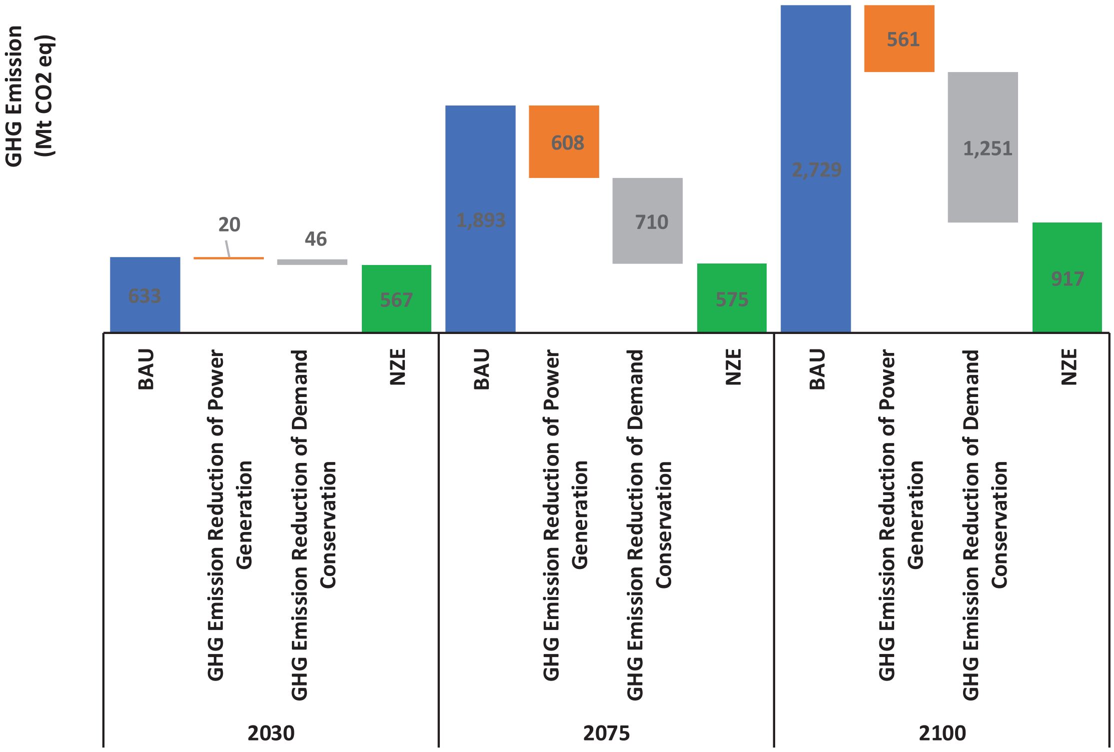

Figure 8: GHG emission reduction from power generation mix and demand conservation in 2030, 2075, and 2100.

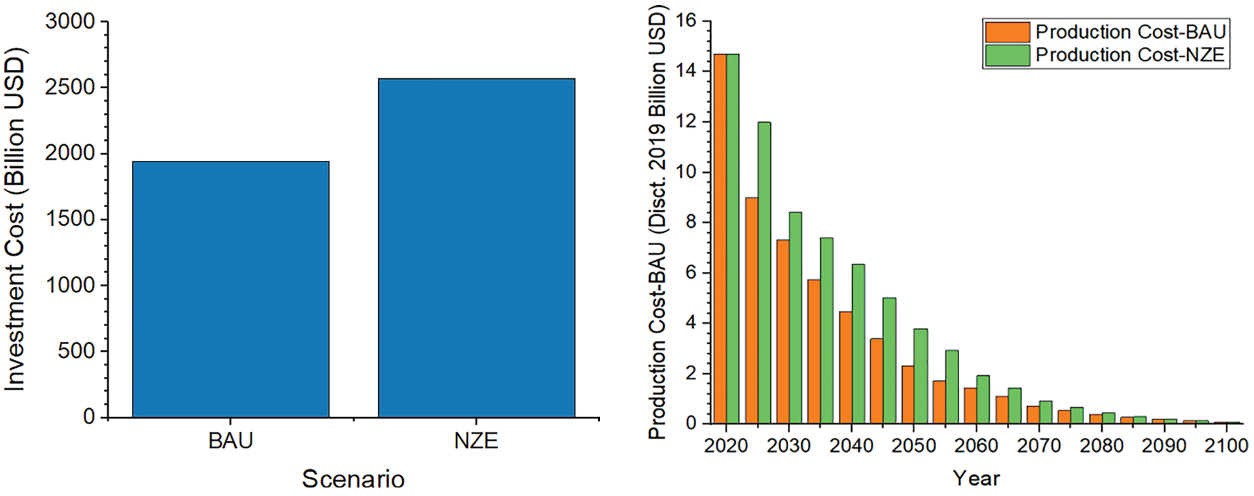

Figure 9: Comparison of total investment cost and total production cost for BAU and NZE scenario conclusion.

it has more fossil fuel power generation in the scenario, shown in Figure 9.

This study aims to achieve Net Zero Emissions (NZE) by reducing the cost of renewable energy, enhancing energy efficiency, and implementing energy conservation measures. The novelty of this researchlies in the exploration of Indonesia's path to net zero emissions without a specific timeline. Through the optimization of power plant combinations in the NZE scenario, it is projected that Indonesia will reach NZE in its power plant energy mix by 2075, approximately 15 years after the government's previous NZE target projections. Despite ignoring policy restrictions, NZE completion will take an extended period due to cost, efficiency, and durability considerations. Various power plants including PV, nuclear, hydro, and biomassare crucial in meeting electricity demand in the NZE scenario. PV power plants are predominant, while other sources like wind, nuclear, hydro, and biomass are essential for peak load energy needs. Battery energy storage systems (BESS) play a significant role in filling energy gaps during off-peak hours.

In the NZE Scenario, a variety of new and renewable energy sources will be able to meet the demand for power beyond 2075. Waste, biogas, and nuclear will also contribute to achieving till the end of the period based on least cost optimization. The use of new and renewable energy is overtaking fossil fuels in power plants. In NZE Scenario, wherein the development of NRE-based power plants is anticipated to progress, there will be a corresponding elevation in investment costs. The cost of production in BAU and NZE scenarios exhibits a gradual decline, in order to enhance competitiveness and promote the transition from fossil-fueled power plants to plants powered by NRE. Consequently, this shift facilitates the achievement of emission reduction targets.

Recommendations

The integration of CCS and CCUS into the optimization of power plants is essential to consider. Nonetheless, careful consideration must be given to the allocation of land for carbon storage in Indonesia. Presently, both CPO and ocean power plants face competitiveness challenges due to their persistently elevated investment costs. Nevertheless, it is strongly suggested to explore other types of new and renewable resources as potential fuels for power plants, like hydrogen, provided that their costs are comparable, in order to meet electricity demand.

Credit Authorship Contribution Statement

Ira Fitriana: Conceptualization, Methodology, Modelling, Data Analysis, Writing, Editing.Hadiyanto:Methodology, Draft Preparation, Review, Editing. Budi Warsito: Draft Preparation, Review, Editing. Edi Hilmawan: Draft Preparation, Review, Editing. Joko Santosa: Methodology, Modelling.

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