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Optimizing Electricity Supply for Jawa-Madura-Bali: Scenarios for Achieving Net Zero Emissions

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Abstract: Nowadays, most of Indonesia's primary energy comes from fossil fuels, which continuously impact the environment. Indonesia continues to push for renewable energy penetration to replace fossil fuels to reducing greenhouse gas (GHG) emissions, especially for electricity generation. This paper aims to create a long-term optimization model for the Java-Madura-Bali (JAMALI) electricity supply. Optimization is carried out with various GHG emission reduction scenarios to achieve net zero emissions (NZE) by 2060 using Low Emission Analysis Platform (LEAP) software. Three scenarios were developed: (1) BAU scenario, a business-as-usual scenario without any new government interventions related to energy policy; (2) PHO scenario, phasing out coal power plant scenario; (3) CCUS scenario, accommodate carbon capture, utilization, and storage without coal power plant phase-out. JAMALI's electricity demand by 2022 reached 60% of the total national electricity demand, of which fossil-based power plants supply more than 85%. Based on optimization, JAMALI's electricity demand, according to the BAU scenario, would be 1072 TWh by 2060. In the BAU scenario, JAMALI does not require electricity imports. However, this leads to a significant increase in CO_2 emissions, from 265 $MtCO_2e$ in 2022 to over 805 $MtCO_2e$ by 2060. The PHO and CCUS scenarios necessitate electricity imports from Kalimantan, Sumatra, and Nusa Tenggara. The total electricity imports in 2060 are projected to reach 180 TWh for the PHO scenario and 162 TWh for the CCUS scenario. The PHO scenario requires the installation of nuclear power plants with a capacity of 21.75 GW by 2060, whereas in the CCUS scenario, the presence of nuclear power plants is not deemed necessary due to the installation of carbon capture, utilization, and storage to the coal power plants. In both scenarios, PHO and CCUS will reach NZE by 2060.

Keywords: LEAP; scenario; net zero emissions; energy transition

1. Introduction

All countries must strive to keep the average global temperature rise below 2°C and limit the increase to 1.5°C[1]. Indonesia has committed to reducing greenhouse gas (GHG) emissions to 31.89% by 2030 through domestic efforts or 43.2% with international assistance[2]. This policy is contained in the Enhanced Nationally Determined Contribution (ENDC) which is in line with the government's policy to achieve net zero emissions by 2060 or sooner[2,3]. The average annual growth of Indonesia's GHG emissions from 2010 to 2030 is projected to reach 3.9% per year if no mitigation measures are implemented[3]. According to the European Commission's report, Indonesia's GHG emissions by 2022 reached 1.24 gigaton CO_2e, with 20.44% originating from the electricity sector[4]. The growth of the population and economy in a region will increase the demand for energy across various sectors[5]. Energy resilience needs to be maintained, particularly electrical energy, which has become a primary necessity for the world's population. The escalating demand for electricity has adverse effects on the environment, given that a significant portion of power generation still relies on fossil fuels. The electricity sector has experienced tremendous progress in the transition to green energy. In 2022, the installed capacity of renewable power plants reached 40% globally, with an addition of 295 gigawatts (GW), marking the most significant annual increase in renewable energy capacity ever recorded[6]. Hydropower remains the most important contributor, with an installed capacity reaching 1,256 GW, or 37% of the global renewable energy mix[6]. Solar photovoltaic (PV) capacity has shown the fastest growth due to its relatively quick installation process[7], with 191 GW installed in 2022, bringing the total installed capacity to 1,047 GW. Wind power has also seen substantial development, reaching a capacity of 836 GW in 2022, a 13-fold increase compared to 2010[6].

Coal remains the primary and most readily available energy source in Indonesia due to abundant[8]. The electricity sector consumed 571 million barrels of oil equivalent (BOE) in 2022, accounting for 37% of the total national fossil energy supply[9]. Indonesia's most extensive electricity system is the Java-Madura-Bali (JAMALI) electricity system, accounting for 70% of the national electricity sales[10,11]. In 2022, the JAMALI electricity system was supported by power plants with a total capacity of 45 GW[12,13]. The high demand for electricity in Java is due to the large industries in the JAMALI region[10]. Unfortunately, the share of renewable power plants in the electricity generation mix is only 10%, primarily sourced from hydropower, geothermal, and solar power plants[11]. Reliable baseload replacement is the main issue when replacing fossil fuels with renewable energy power plants. Nuclear power plants can be the solution[13], but in Indonesia, it remains the last resort for implementing renewable energy for electricity generation due to concerns related to safety, radioactivity, and high economics[14].

The most extreme option in the effort to reduce GHG emissions is the phase-out of coal power plants and their replacement with renewable energy sources. This transition must consider various aspects, including institutional, economic, technical, and social considerations[15,16]. A strategy for coal phase-out can be implemented by accelerating market-based decommissioning or specifying a specific decommissioning pathway based on the operational lifespan of coal power plants[17]. Carbon capture, utilization, and storage (CCUS) technology can solve the coal phase-out scheme within the electricity sector[18,19]. The combination of scenarios involving the phase-out of coal power plants that have reached the end of their lifespan and the implementation of CCUS in active plants can significantly impact carbon emissions reduction[20].

Germany, the UK, the US, Poland, and Australia are among the nations that have gained experience in coal phase-out[17,21]. In 2021, the Polish government agreed with mining unions to close all coal mines by 2049[21]. According to Tiedemann et al.'s[17] research, the gradual cessation of around 10 GW of coal power plant capacity imposed a financial burden of approximately 700 million EUR on German taxpayers (678 ± 51 million EUR). A coal phase-out auction system emerges as the most effective option amidst policies of increasing CO_2 prices (around 2.4 ± 0.2 EUR/tCO_2), which is considered less restrictive for businesses in discontinuing coal power plants[17].

The increasing interest in the contribution of CCUS to emissions reduction has prompted numerous countries to adopt and implement such technologies. Currently, the United States, supported by incentives and policies, stands as the global leader in CCUS, boasting a capture capacity of over 25 Mt/year, which constitutes 60% of the global capacity, with only half of the planned capacity currently in operation. China is gearing up to construct the most extensive CCUS facilities, aiming to capture about a quarter of the total cumulative CO_2 by 2070. The largest CCUS projects in Europe, are in Norway and can capture 1.7 MtCO_2/year. There are 11 other projects in various stages of development across Europe, with a combined capture capacity reaching 30 MtCO_2/year[22].

The diverse challenges of developing each type of renewable power generation drive researchers to engage in sustainable energy planning to create access to clean, affordable, and reliable energy as a foundation for prosperity and economic growth[23]. Several energy modeling software tools are commonly employed, such as MARKAL-TIMES, POLES, NEMS, ERIS (Energy Research and Investment Strategies), GALLM [24], and LEAP (Low Emission Analysis Platform)[25]. The MARKAL-TIMES, POLES, and NEMS models are based on partial equilibrium simulation, signifying that the conditions of the quantity and price of energy commodities are in equilibrium[24,26–27]. ERIS is a bottom-up multi-regional energy system optimization model that accommodates the impacts of alternative policy instruments on the diffusion of energy technologies and various sustainable development indicators, including climate change, energy supply security, and transportation[28]. GALLM employs mixed-integer linear programming, wherein the total cost of electricity supply is minimized to achieve specific electricity demand levels over time[29].

LEAP, a platform developed at the Stockholm Environment Institute, is a tool available under a free license for government and non-profit use. However, for other use cases, a license must be purchased. LEAP is an integrated energy model which supports demand modeling with both bottom-up energy technology rich model and top-down approaches, combining these two approaches. On the supply side, LEAP assists in accounting, simulation methods, and capabilities for optimization modeling. Additionally, LEAP facilitates analyses across multiple regions and trade between regions and energy storage modeling capabilities[30]. Several studies in various countries have utilized LEAP, including the transport system in Nigeria[31], energy modeling for the postindustrial city of Shenzhen, China[23], household sector energy modeling in India[32], energy modeling in Bulgaria[33], long-term electricity demand forecast and supply side scenarios for Pakistan[34], energy planning in West Java, Indonesia[35], and decarbonization pathways for power generation in Sumatra, Indonesia[36].

Several studies on energy modeling in Indonesia have been conducted, and this research aims to provide a distinct perspective, constituting the novelty of this journal, as shown in Table 1. Based on previous research (Table 1), the existing research gap is that there has been no simulation research on the optimization of sustainable electricity energy transformation from 2019 to 2060 specifically carried out for the JAMALI region to support Indonesia's NZE target in 2060. The contribution of this research is its comprehensive coverage, addressing not only sustainable energy transition on the supply side but also exploring energy transition from a demand perspective in the JAMALI region to support Indonesia's net zero emissions by 2060.

2. Methodology

LEAP is currently the most widely used due to its flexible nature and wide range of applications, not only models at the sectoral and regional levels but also at the national level[23)]. Moreover, LEAP has a user-friendly interface, facilitating ease of use for novice researchers. In contrast to other models, the LEAP model enables a more intricate examination of individual urban sectors, aiding in developing a comprehensive plan[37)].

This study relies mainly on simulation using LEAP to assess the electrical demand in JAMALI and examine the corresponding supply aspects to meet such requirements by considering GHG emission reduction to achieve net zero emissions (NZE) by 2060. The flexibility inherent in LEAP, coupled with its energy accounting function, enables the alignment of electricity demand with supply-side generation. Furthermore, LEAP provides comprehensive information regarding system impacts, encompassing electricity generation from diverse sources, installed capacity requirements, cost parameters, and environmental emissions.[34)].

2.1. LEAP Modeling Framework

The LEAP-JAMALI-Power model aims simulates the long-term planning of the power generation system from 2023 to 2060, using historical data from 2019 to 2022 as the base year. Indonesia has a very wide territory, consisting of multi-regions with different characteristic, and has minimum data availability. LEAP is a modeling tool that can be used to simulate the production, consumption, and extraction of energy resources in various economic sectors across multi-regions. The LEAP optimization model considers variables that can fluctuate over time across different regions and economic sectors, including those influenced by changes in assumptions about power generation policies and technology. Scenarios can be created and compared with other scenarios to analyze the costs, benefits, energy requirements, and environmental impacts of each. LEAP integrates demand and optimizes supply based on a least-cost power system[25)]. Using its optimization methodology,

Table 1. Comparison of research with prior similar studies

Author	Title	Method/ Software	Scenarios	Year	Demand Side	Supply Side
Handayani et al.[42)]	Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia	LEAP	Reference Scenario (REFF), Natural Gas Scenario (NGS), Renewable energy scenario (REN), Optimization scenario (OPT)	2016-2030		Least-cost function, not acomodating inter-region connection
Sarjiya et al.[10)]	Achieving New and Renewable Energy Target: A Case Study of Java-Bali Power System, Indonesia	MoMANI-OSeMOSYS platform	BAU, RE, N&RE	2018-2030	Singgle demand projection for all scenarios	Least-cost objective function, not acomodating inter-region connection
Sarjiya et al.[5)]	Assessing Potential Scenarios for Achieving New and Renewable Energy Targets in Java-Bali Power System, Indonesia	OSeMOSYS platform	BAU, NRE, NRE with nuclear as the last option, Interconnection BAU, Interconnection NRE, and Interconnection NRE with nuclear as the last option	2020-2050	Singgle demand projection for all scenarios	Least-cost and acomodating inter-region connection
Dwijatmiko et al. (This paper)	Optimizing Electricity Supply for Jawa-Madura-Bali: Scenarios for Achieving Net Zero Emissions	LEAP	BAU, PHO, CCUS	2019-2060	Divergent demand between BAU and PHO-CCUS scenarios stem from the optimization of energy transition within the demand side.	Least-cost function, prioritize base load power plants followed by peaker power plants, and acomodating inter-region connection.

LEAP can also identify the most cost-effective power generation option by minimizing the total expense over the entire projection period. With these various advantages, LEAP was chosen as a model to answer the electricity transformation by supporting net zero emissions by 2060.

Key assumptions are key drivers for the energy model, encompassing demographics, macroeconomic factors, energy intensity, fuel share, and energy-related policies[30,34]. Energy demand will be segmented based on the Handbook of Energy & Economic Statistics of Indonesia (HEESI) 2022 data, covering sectors such as industry, transportation, households, commercial enterprises, other sectors, and industrial raw materials[9]. Each sector will exhibit distinct sub-sectors with diverse energy characteristics. Gross domestic product (GDP), the industry's aggregate output, and a region's total population delineate the activity level. Industrial activity levels are often indicated by the industrial value-added obtained from the GDP[38].

Total energy consumption is the product of activity level and energy intensity[25]. In the household sector, energy intensity is defined as helpful energy divided by the efficiency of appliances. Each electronic device in households has a distinct energy efficiency value. Technological advancements continuously enhance efficiency, potentially decreasing future energy intensity in the household sector. This reduction in energy intensity is expected to result in a decline in energy demand. In the transportation sector, the distance traveled by vehicles is employed as the activity level to quantify energy consumption. The projection of the vehicle count is computed based on the previous year's stock, current-year sales, and the operational lifetime of automobiles, buses, trucks, and motorcycles. The vehicle's operational lifetime is linked to its survival rate, which is expressed through an S-curve function. The sales of vehicles are modeled using a logistic function[39]:

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

$$r_t = K_a * e^{(-K_b*(t-1)+ C_{t-1}*K_c)} \tag{2}$$

Where S is the number of vehicle sales, r is vehicle sales growth, t is year, C is GDP per capita growth, K_a is the regulator factor for early growth, K_b is the speed factor to achieve final growth, and K_c is the regulator factor for final growth. The electricity demand forecast structure for all sectors is illustrated in Fig. 1.

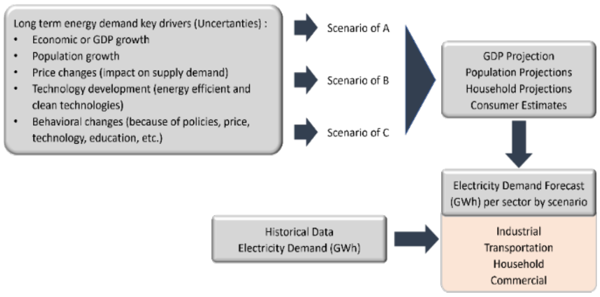

Fig. 1. Electricity demand forecast structure

In the transformation module of the LEAP-JAMALI-Power model, considerations will encompass electricity generation, transmission, and distribution. Electricity generation will involve current technologies and feasible future technologies applicable in Indonesia. A distinction will be made between primary and secondary energy resources within the resource module. Primary energy resources include coal, biomass, solar, hydro, wind, and natural gas. Secondary resources comprise gasoline, liquefied petroleum gas, diesel, electricity, and heat. The structure of the LEAP-JAMALI-Power model is depicted in Fig. 2. The figure illustrates how this research model is separated into four modules: demand module, transformation module, resources module, and key assumption module. The LEAP demand module is used in energy demand analysis to calculate the expected energy demand for each scenario in four economic sectors, including the industrial, transportation, household, and commercial sectors. The LEAP transformation module is used in power generation analysis to calculate the total power generation capacity required to meet the demand as well as the total output produced by the power plant.

The resource module is used to identify the availability of energy resources required to meet the energy demand for each economic sector. The key assumptions are the parameters and variables that drive estimates of future demand projections. All the power generation listed is implemented. Some are implemented in the BAU scenario, others in the PHO scenario or CCUS scenario. The technologies did not appear all at once, but some were implemented at the beginning, middle, or near the end of the projection. Explanations have been added to the manuscript.

Optimization using the minimized cost of objective function with constraint variables including resources, emissions and policies. Power plants with the capability to function as base load will be given priority over those serving as peakers[25,38]. Capacity restrictions for power generation can be imposed through logical assumptions or by adhering to established energy policies. Several energy policies used in the LEAP-JAMALI-Power model are presented in Table 2[3,11,40,41].

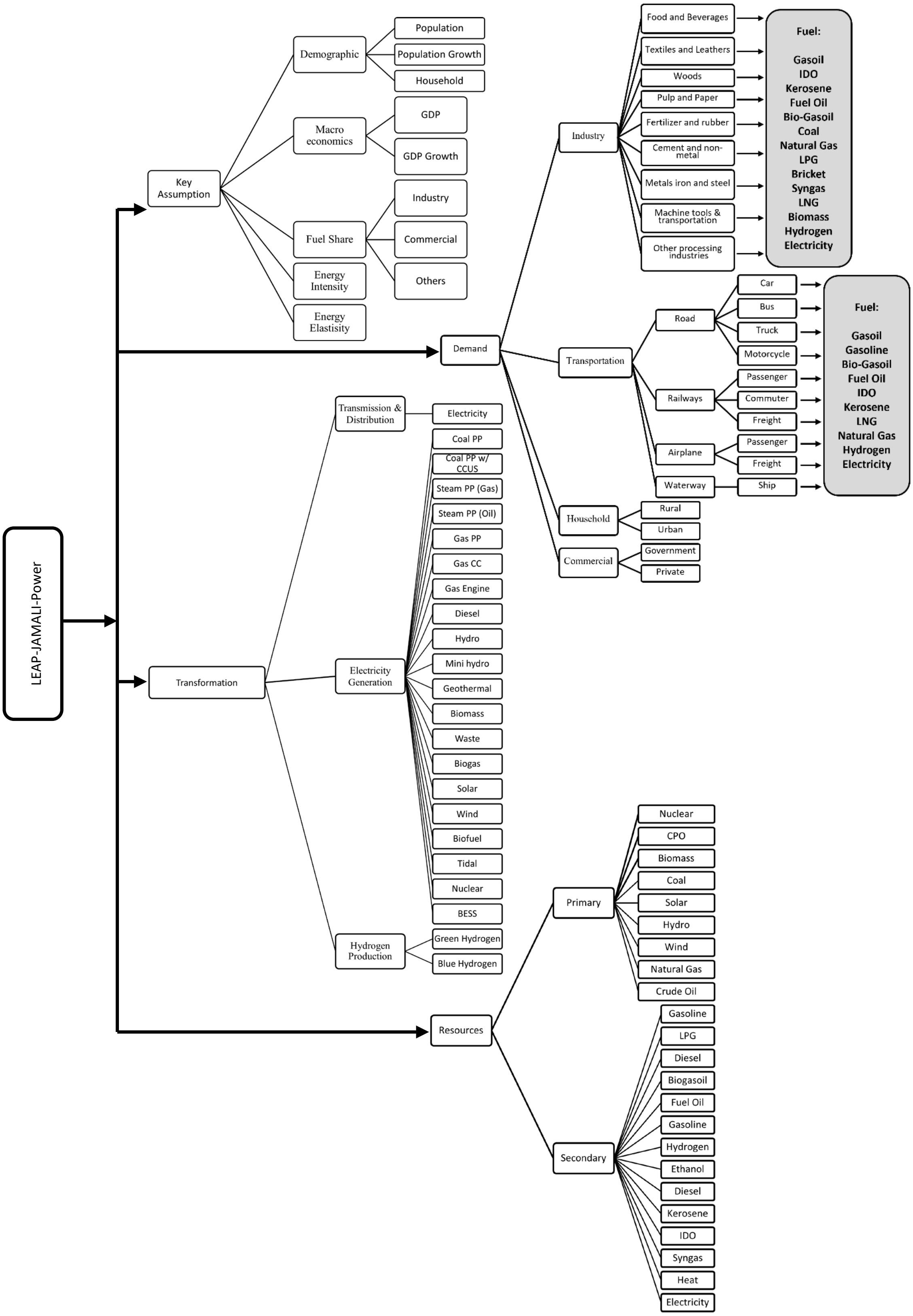

Fig. 2. Energy planning flow for the LEAP-JAMALI-Power model

Table 2. Indonesia's energy policy as the reference

Year	Policy	Institution	Focus	Key Feature and Targets	Application of Regulations in Scenarios
2014	Regulation of Government of The Republic of Indonesia No 79 of 2014	National Energy Council (DEN)	Guidelines for national energy management (National Energy Policy/KEN)	Targeting the use of renewable energy to reach at least 23% of the national primary energy mix by 2025 and reach 31% by 2050.	BAU, PHO,CCUS
2017	Presidential Regulations Number 22 of 2017	National Energy Council (DEN)	Elaboration of cross-sector KEN implementation plans	Targeting the use of renewable energy to reach at least 23% of the national primary energy mix by 2025 and reach 31% by 2050.	BAU, PHO,CCUS
2021	RUPTL 2021-2030	Ministry of Energy and Mineral Resources and PT. PLN (Persero)	10-year electricity development plan for the operating areas (2021 to 2030)	The target for renewable energy capacity in the power generation sector by the year 2030 is set at 51%. The addition of renewable energy facilities is projected to reach an increase, encompassing various sources such as solar photovoltaic, geothermal, wind, hydropower, and others.	BAU, PHO,CCUS
2022	ENDC	Government of Republic Indonesia	Indonesia's commitment to reducing GHG emissions	Targeting GHG emissions reduction until 31.89% by 2030 through domestic efforts or 43.2% with international assistance.	PHO,CCUS
2022	Presidential Regulations Number 112 of 2022	Government of Republic Indonesia	Accelerating the Development of Renewable Energy for Providing Electric Power	Restrictions on additional coal power plant capacity, operating until 2050 at the latest. Acceleration of the coal power plants phase-out, development of renewable power plants, and electricity pricing policy.	PHO,CCUS

2.2. Scenario

The scenarios are a collection of assumptions within the impact model, analyzed for the energy system. To facilitate analysis, the differences in assumptions between one scenario and another typically reside in only a few variables. This study analyze the impact of three scenarios on the transformation of JAMALI's electricity system to zero-emission by 2060. The scenarios used in this study are detailed in Table 3.

2.3. Base Data and Assumptions

All driving variable data are collected to estimate electricity demand in the JAMALI system annually in 2022 with a year-end projection for 2060. The base year is used to begin the calculation of all driving variables that determine the optimal scenario for the provision of electricity in the JAMALI system. All data and information were obtained from agency-related sources, and the demographic and macroeconomic data obtained from the Central Statistics Agency (BPS) serve as the primary drivers determining the projections for electricity demand. For this study, the population census data in 2020, as presented in Table 4, are utilized[43].

The existing power generation data for 2022 in the JAMALI region has been processed based on 2022 PLN Statistical data, Electricity Supply Business Plan (RUPTL) 2021-2030, and HEESI 2022, which will serve as the initial reference for the addition or reduction of electric power generation capacity in the future by the adopted policies and scenarios[9,11,12]. The electricity system in JAMALI in 2022 will still predominantly be fueled by fossil power generation, as evidenced by the information presented in Table 5.

3. Result

3.1. Electricity Demand Projection

JAMALI has the largest share of electricity in Indonesia because the numerous industries that constitute an energy-intensive sector. According to the Business as Usual (BAU) scenario, JAMALI's electricity demand is projected to increase from 218 TWh to 1072 TWh, while according to the PHO and CCUS scenarios, it becomes 820 TWh, as shown in Fig. 3. Industrial power continues to dominate electricity demand, accounting for more than 40%, with a breakdown of 429 TWh in the BAU scenario and 352 TWh in the PHO and CCUS scenarios. In the transportation sector, the widespread adoption of electric vehicles in the PHO and CCUS scenarios increases electricity demand from 0.3 TWh in 2022 to 171 TWh in 2060. 2060. Meanwhile, the electrification program in the BAU scenario is less extensive, resulting in electricity demand for the transportation sector reaching only 103.8 GW. The difference in energy demand is attributed to the PHO and CCUS scenarios, which consider the increased efficiency

Table 3. Scenarios of LEAP-JAMALI-Power model

Scenarios	Demand Projection	Supply Side	
		Objective	Main Resources
BAU: Bussiness as Usual	• There is no increase in the equipment efficiency.	Followed the current government's plan and policy, no new government interventions related to sectoral energy policies	As per the existing government's plan and policy.
PHO: Coal Power Plant Phase-out	• Accommodating increased equipment and technology efficiency that can reduce useful energy.	Implementation of the coal phase-out policy periodically for all coal power plants until 2060	• Renewable energy resources (solar, wind, hydro, geothermal, and biomass) and Nuclear. • Allows electricity trading from Kalimantan, Sumatera, and Nusa Tenggara.
CCUS: Coal Power Plants with CCUS	• Accommodating increased equipment and technology efficiency that can reduce useful energy.	• Implementation of a coal phase-out policy for coal power plants that have reached operational limits. • Application of CCUS to coal power plants that have not yet reached operational limits	• Renewable energy resources (solar, wind, hydro, geothermal, and biomass) and implementing CCUS, nuclear energy is ignored. • Allows electricity trading from Kalimantan, Sumatera, and Nusa Tenggara to JAMALI.

Table 4. Historical demographic data and projections from 2019 to 2060 for the JAMALI region

Parameter	2019*	2020*	2021*	2022*	2030	2040	2050	2060	Average annualygrowth rate (%)
Population (million people)	154.5	155.9	157.2	158.4	167.6	175.2	178.5	179.5	0.4%
Households (million)	41.7	42.1	42.4	42.8	45.4	47.6	48.7	49.2	0.4%
GRDP per capita (million rupiahs) at constant price in 2010	42.9	41.3	42.4	44.3	63.8	113.6	177.9	258.4	4.5%
Urbanization ratio (%)	65.7	66.5	67.3	68.9	74.2	80.8	84.5	85.7	0.65%

Table 5. Existing power plant data of the JAMALI region by 2022

Power Plants	Capacity (MW)	Fuel Consume (Thousand TOE)	Generation (GWh)	Capital Cost (Thousand USD/MW)	Fix Cost (Million USD/MW)	Variable Cost (USD/MWh)	Efficiency (%)	Max. Availability (%)
Coal	28,582.5	15,550.49	180,852.26	1,400	41.2	0.1	25.5	72.23
Steam (Gas)	900	81.68	950	1,400	41.2	0.1	30.0	12.05
Steam (Oil)	900	15.47	180	1,400	41.2	0.1	30.0	2.28
Gas	3,260.4	369.22	4,294.08	700	23.3	0.1	30.0	15.05
Gas CC	10,383.7	2,901.64	33,746.07	750	23.3	0.1	44.0	37.09
Gas Engine	212.7	77.78	904.68	700	8	6.4	40.0	48.56
Diesel	311.2	42.64	496.01	800	8	6.4	40.0	18.19
Hydro	2,647.5	1,148.52	13,357.29	2,000	37.7	0.7	33.0	57.59
Mini Hydro	182.9	2.98	34.71	2,600	53	0.5	33.0	2.16
Geothermal	1,253.8	863.56	10,043.51	2,500	18	0.3	33.0	91.44
Biomass	217.1	137.57	1,600	1,700	47.6	0.1	33.0	84.11
Waste	28.5	0.94	11	2,500	125	3.0	25.0	4.41
Biogas	2	1.29	15	2,100	97	0.1	35.0	85.61
Solar	32.2	2.45	28.52	1,200	15	0	18.0	10.12
Wind	1.4	0.43	5	1,600	60	0	25.0	41.36
Coal with/ CCUS	-	-	-	2,800	120	0.4	35.0	-
Gas CC with/ CCUS	-	-	-	1,500	65	0.3	46.0	-
Hydro Pump Storage	-	-	-	1,500	37.7	1.3	33.0	-
Biofuel	-	-	-	800	8	6.4	40.0	-
Tidal	-	-	-	5,000	150	0	25.0	-
Nuclear	-	-	-	5,000	100.889	0.314	33.0	-
BESS	-	-	-	1,400	37.109	0	85.0	-
Total	**44,915.8**	**21,196.744**	**246,518.13**					

of equipment and technology, whereas the BAU scenario does not. In the household sector, the improved efficiency of electric appliances in the PHO and CCUS scenarios will reduce electricity demand by up to 50% compared to the BAU scenario by 2060. The same trend is observed in the commercial sector, where electricity demand in the PHO and CCUS scenarios is 39% lower than in the BAU scenario, as shown in Fig. 4.

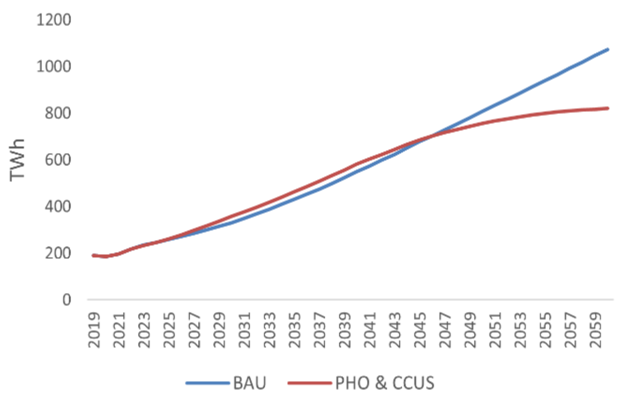

Fig. 3: Total electricity demand projection by scenario

3.2. Power Generation Capacity Projection

BAU Scenario

In the BAU scenario, there are no restrictions on fossil fuel power plants, leading to an increase in capacity in line with the growing electricity demand in JAMALI. The power plant capacity in 2060 is projected to reach 247.5 GW, up from 49 GW in 2022, growing at approximately 4% annually. Coal power plants still dominate the capacity share of power plants, reaching 99 GW or 40% of the total capacity in 2060, followed by gas combined cycle at 19%, solar at 18%, battery energy storage systems (BESS) at 5%, wind at 4%, hydro at 3%, geothermal at 2%, other fossil power plants at 6%, and the remaining 4% consisting of other types of renewable power plants. The significant capacity of coal power plants is due to their lower generation cost, making them a preferred choice without restrictions. With the continued operation of coal power plants, nuclear power plants are not considered in the BAU scenario. The total capacity and mix of power plants in JAMALI in 2060 are illustrated in Fig. 5.

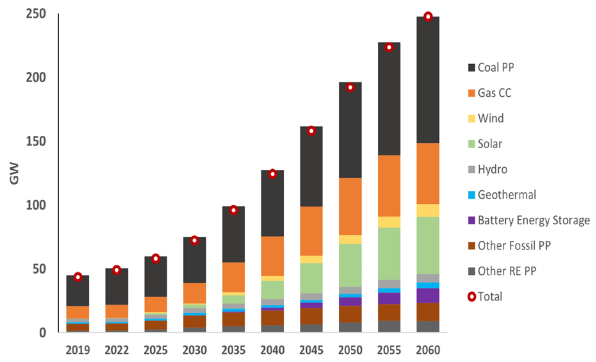

Fig. 5. Power plant capacity projection from the BAU scenario

PHO Scenario

Coal power plants will continue to increase until 2030, following the energy model based on RUPTL for 2021-2030. Subsequently, periodic phase-out programs for coal power plants are implemented, leading to a gradual decrease in capacity until it reaches zero in 2060, with an estimated capacity reduction of 6.71% yearly. Because of the absence of fossil power plants in the power plant mix, replacement power plants are needed to play the base load role. One emerging base load power plant is the nuclear power plant (NPP), which will begin on-grid operations in 2032 with an initial capacity of 0.75 GW and will increase steadily to 21.75 GW by 2060.

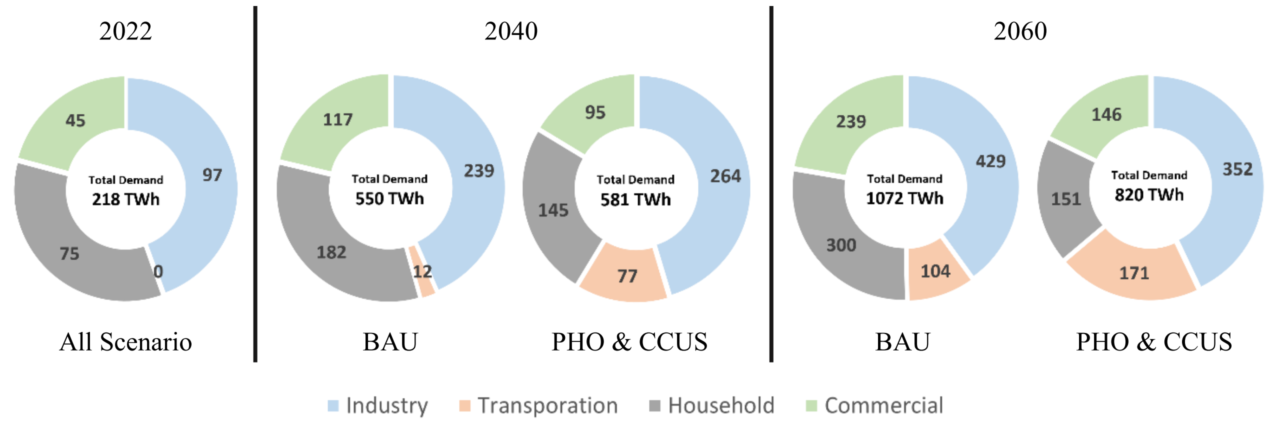

Fig. 4. Electricity demand projection by sector

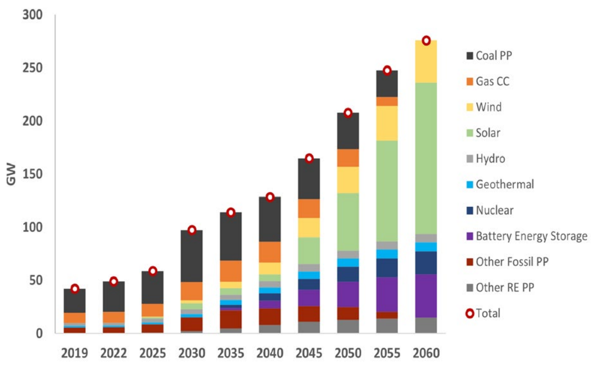

Fig. 6. Power plant capacity projection from the PHO scenario

In addition, BESS is crucial as a baseload substitute, especially with the rising capacity of renewable energy power plants, primarily solar and wind. The BESS capacity will reach 40.6 GW in 2060, supporting photovoltaic power plants with a capacity of 142.2 GW and wind power plants with a capacity of 40 GW.

Based on data, the renewable energy potential in JAMALI is insufficient to meet its electricity needs, necessitating the import of electricity from other regions[11]. NPPs cannot be installed in JAMALI due to social and political issues. Therefore, transmission cables must transmit electricity generated by NPPs from Kalimantan and Sumatra to JAMALI. Electricity imports from Sumatra and Kalimantan begin in 2045 with capacities of 0.9 TWh and 0.47 TWh, respectively, increasing to 117 TWh and 54 TWh by 2060. The electricity supply for Kalimantan is projected to come mostly from hydropower and wind power plants. In addition to Kalimantan and Sumatra, Nusa Tenggara is also an electricity exporter to JAMALI due to its significant solar power plant potential. Electricity exports to JAMALI from Nusa Tenggara will reach 9 TWh in 2060. The scenario of electricity imports and exports is illustrated in Fig. 7.

CCUS Scenario

The implementation of CCUS in coal power plants will begin in 2045 with an initial capacity of 0.2 GW. It will continue to increase to 27.6 GW by 2060, coinciding with the phase-out of coal power plants without CCUS in the power plant mix of JAMALI. The addition of CCUS technology increases the cost of electricity generation from coal power plants, affecting the overall power plant mix. In the CCUS scenario, the mix of solar power plants remains the largest, followed by BESS and wind power plants, with capacities of 139.4, 40.6, and 40 GW, respectively. Because the role of baseload is still covered by the CCUS and BESS coal power plants, nuclear power plants, which have high electricity generation prices, are not considered in this scenario. Other fossil fuel power plants, besides coal power plants, will also experience a decline in capacity until reaching zero by 2060. Gas combined cycle power plant experiences a capacity decrease starting in 2041 with an average annual decrease

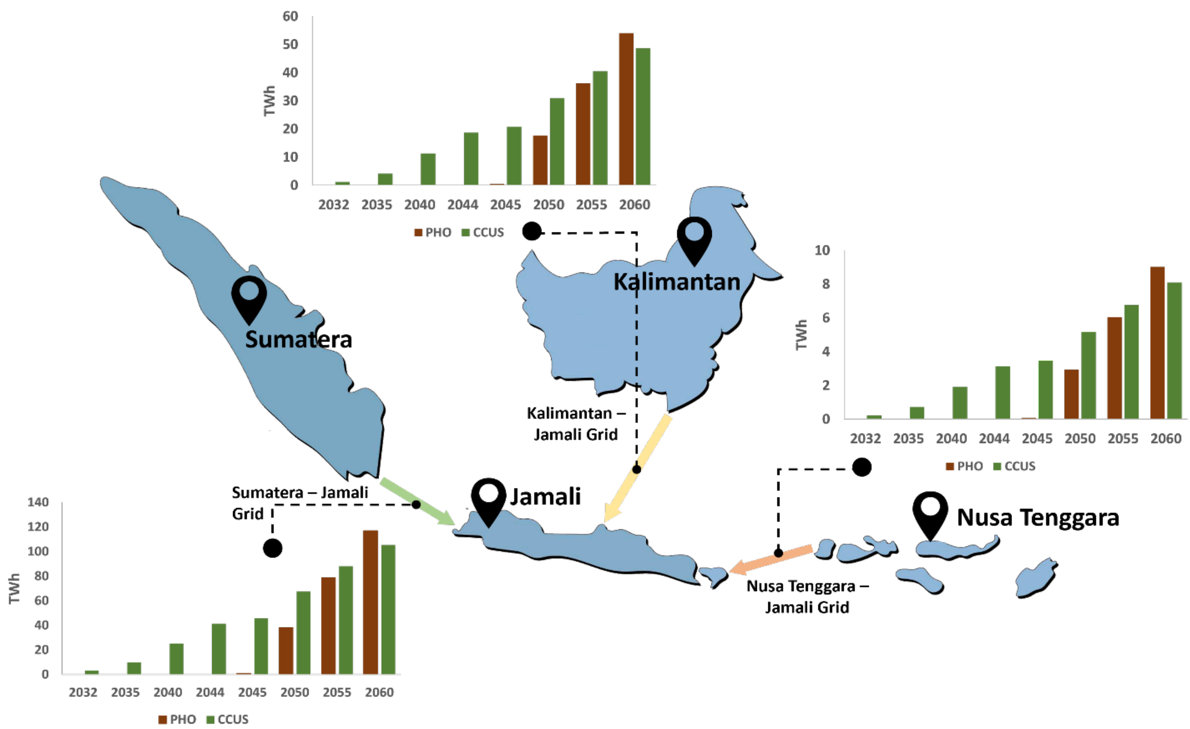

Fig. 7. Electricity trading the PHO and CCUS scenarios

of 0.97 GW, while the mix of gas turbine power plants and gas engine power plants begins to decrease in 2036 with average annual decreases of 0.35 GW/year and 0.28 GW/year, respectively. The power plant capacity based on the CCUS scenario is depicted in Fig. 8.

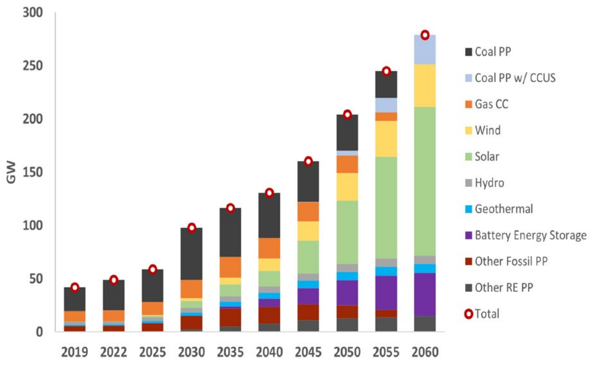

Fig. 8. Power plant capacity projection from the CCUS scenario

In the CCUS scenario, electricity imports from Kalimantan, Sumatra, and Nusa Tenggara are still needed. The import capacity is smaller than in the PHO scenario, totaling 162 TWh in 2060. However, the electricity import-export activity will commence in 2032, 13 years earlier than the PHO scenario. Imports from Sumatra remain the largest, reaching 75% in 2032 and 65% in 2060, with a total of 105.3 TWh, followed by imports from Kalimantan at 48.6 TWh and from Nusa Tenggara at 8.1 TWh in 2060, shown in Fig. 7.

3.3. Projection of GHG Emissions

GHG emissions are projected to continue increasing without actions to enhance the capacity of renewable energy in the electricity sector. According to the BAU scenario, GHG emissions by 2030 are estimated to reach 290 million tons of CO_2e and 805 million tons of CO_2e by 2060. This condition would hinder the achievement of targets set in the ENDC, which aims for the energy sector to contribute 12.5% to GHG emission reductions (approximately 358 million tons of CO_2e) by 2030[3].

In the PHO and CCUS scenarios, emissions will not be significantly reduced by 2030, with only a marginal difference of approximately 5 million tons of CO_2e compared to the BAU scenario. However, in the long term, both scenarios will result in zero emissions in the electricity sector by 2060. GHG emission reduction between the PHO and CCUS scenarios has different pathways because of the differences in the power plant mix. According to the PHO scenario, the peak GHG emissions occur in 2040, whereas in the CCUS scenario, the peak occurs in 2043. After these years, GHG emissions will continue to decline, averaging 19.6 million tons of CO_2e for the PHO scenario and 21.25 million tons of CO_2e for the CCUS scenario. The GHG emission projection is illustrated in Fig. 9.

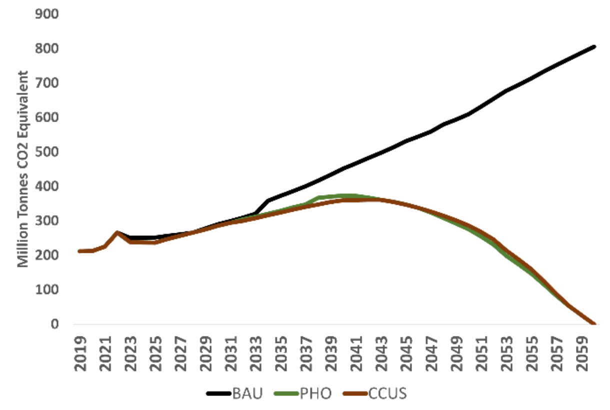

Fig. 9. GHG emissions projection

3.4. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is a measure that can be used to evaluate the long-term economic viability of the overall power generation system. The calculation of LCOE involves several factors, initial investment costs (*I*), operational and maintenance costs (*M*), fuel costs if applicable (*F*), and electrical energy production (*E*). *t* represents the number of years the power plant operates until it reaches its economic lifespan (*n*) and the applied rate of return or discount rate (*r*) is assumed to be 10% for developing countries such as Indonesia. The LCOE calculation for each power plant is given by Equation 3.

$$LCOE = \frac{sum\ of\ cost\ over\ lifetine}{sum\ of\ electrical\ energy\ production\ over\ live\ time} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (3)$$

The LCOE accounts for 70% of the total costs incurred by the power generation company, while the remaining 30% consists of transmission and distribution costs.

The LCOE for the total electricity system is illustrated in Fig. 10. The BAU scenario has lower generation costs than the PHO and CCUS scenarios. Starting in 2030, the LCOE gap between the BAU and the other two scenarios will widen, reaching approximately 18.0%. This can be attributed to the initiation of the energy transition process, where more expensive low-carbon generation technologies replace conventional coal power plants. By 2060, this LCOE gap will further increase, reaching 19.6% for the PHO scenario and 24.5% for the CCUS scenario compared with the BAU scenario. This gap is widening because of stricter GHG reduction targets to achieve net-zero emissions. Paying serious attention to this increase in LCOE is crucial to ensure that the energy transition process continues to provide fair and affordable access to all layers of society.

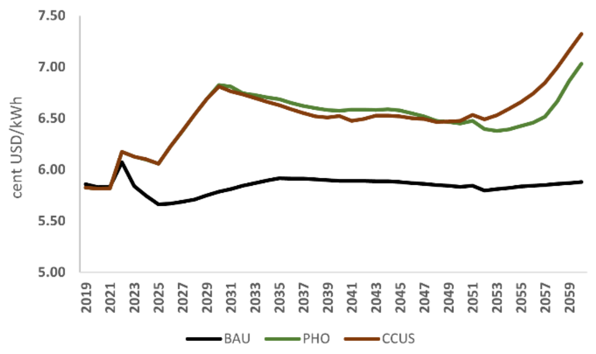

Fig. 10. Comparison of the total generation costs for each scenario

4. Conclusion

Optimizing the JAMALI electricity transformation is crucial for Indonesia to achieve net-zero emissions by 2060. This requires technological advancements, policy reforms, and stakeholder collaboration. Transitioning to renewable energy sources like solar, wind, and hydro, along with innovative grid technologies, will significantly reduce carbon emissions in the electricity sector. By taking a holistic and collaborative approach, Indonesia can lead in sustainable energy while promoting economic growth and environmental stewardship.

Reducing GHG emissions from 805 $MtCO_2e$ in the BAU scenario to zero will increase the LCOE by 19.6% in the PHO scenario and 24.5% in the CCUS scenario. A carbon tax could help mitigate this cost increase. The PHO scenario, despite achieving net zero by 2060, offers a lower LCOE than the CCUS scenario. To achieve this, Indonesia needs to start operating NPPs by 2032 and BESS by 2031, with capacities reaching 21.7 GW and 40.6 GW by 2060, respectively. Further research on public acceptance of NPPs is necessary for the PHO scenario.

The CCUS scenario does not require NPPs, as CCUS power plants handle the baseload, reducing potential social issues with NPPs. CCUS implementation starts in 2045, and BESS operations begin by 2030. Both PHO and CCUS scenarios eliminate coal power, necessitating electricity imports to JAMALI from Sumatra, Kalimantan, and Nusa Tenggara. In the PHO scenario, imports start in 2045 at 1.5 TWh and reach 180 TWh by 2060. In the CCUS scenario, imports begin earlier in 2032, reaching 162 TWh by 2060. Future research should expand to include a broader range of energy sources, such as fossil fuels, industrial raw materials, and fossil fuel production. This comprehensive examination of all energy sectors will help Indonesia meet its target of 34% renewable energy utilization by 2030.

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