Optimization of Energy Mix to Achieve Bali Net Zero Emission 2045

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Abstract The government of Bali Province has announced to achieve Net Zero Emission (NZE) target by 2045; therefore, energy transition strategy currently becomes a challenge for the government. An accelerated implementation of renewable energy (RE) power generation was introduced as part of the strategy. This study is focused on the investigation of energy mix optimization for power generation using the Low Emission Analysis Platform (LEAP) software. The analysis was carried out for a period of year 2025 to 2045. Three scenarios were introduced for the analysis, namely optimistic, moderate, and pessimistic. The three scenarios were differentiated based on energy policies, technology penetration levels, and decarbonization targets at national and regional levels. The model was validated using actual energy consumption data and then simulated to project electricity demand and power generation mixture. The analysis results show that with the optimistic scenario, the proportion of RE supply could reach 51.1% in 2045, dominated by solar PV and geothermal power, following the complete phase-out of coal-fired and diesel power plants. The moderate scenario introduces an RE proportion of 19.3%, with a slightly slower transition acceleration. The pessimistic scenario however; indicated that the fossil fuel power plant may be still in use until the end of year 2045, with RE contribution of about 7.4%, reflecting a condition without accelerated energy transition. The analysis results thus conclude that to achieve Bali NZE in 2045, it is necessary to implement a strategy that accelerating the RE investment, strengthening supportive policies, and gradual phase-out of fossil-fuel power plants.

***Index Terms*—Bali, Energy mix, LEAP, Net Zero Emission, Renewable energy.**

I. Introduction

The island of Bali, known as one of Indonesia's main tourist destinations, has experienced a significant increase in electricity consumption, which is in line with the growth of the economy, tourism, and related industries. Currently, Bali electricity system is still heavily dependent on fossil fuels, both from power plants operating in the region and from interconnection with Java Island. This reliance poses a major challenge in the transition toward a more environmentally friendly energy system, in line with the local government's commitment to achieve Net Zero Emissions (NZE) by 2045. Beyond environmental concerns, the dominance of fossil fuels also creates vulnerability to fuel price fluctuations and threatens energy security [1].

Optimizing the energy mix of power plants is an important strategy in supporting the transition to sustainable energy. With the optimized energy mix, not only a reduction in greenhouse gas emissions is accomplished, but also an improvement in the reliability of the electricity system. In addition, independency on a single type of energy source may also be achieved. In Bali, renewable energy (RE) sources such as solar power, geothermal energy, and biomass offer significant opportunities to gradually replace the role of fossil fuels. Policies at both the national and regional levels, such as Bali Governor Regulation No. 45/2019 regarding Clean Energy in Bali, serve as regulatory frameworks to accelerate the adoption of RE [2].

This study aims to analyze and optimize the energy mix of power plants in Bali Island for the period of 2025–2045, to achieve the 2045 NZE target. Modeling was carried out using the Low Emission Analysis Platform System (LEAP) software to simulate three energy transition scenarios, namely optimistic, moderate, and pessimistic. The analysis includes projections of electricity demand, installed power generation capacity, and the contribution of each energy source to the total energy mix.

The innovation of this research lies in the modeling of long-term energy mixes integrated with regional decarbonization targets, as well as a multi-scenario approach that provides a comprehensive picture of possible energy transition master plan for Bali. Results of this study will be beneficial in providing strategic approach for local governments, electricity providers, and other stakeholders in designing effective policies and investment plans for power plants to achieve NZE 2045.

II. Literature Review

A. Energy Policy and Targets

Indonesia's energy policy is based on the National Energy General Plan (RUEN) established through Presidential Regulation No. 22/2017. This plan sets targets for new and renewable energy (NRE) of 23% by 2025 and 31% by 2050. These targets are reinforced by the Regional Energy Master Plan (RUED) of Bali Province, which adopts a vision to reduce greenhouse gas emissions, in line with Indonesia's Nationally Determined Contribution (NDC) under the Paris Agreement [3].

The Bali Provincial Government issued Bali Governor Regulation No. 45/2019 on Clean Energy in Bali. This regulation promotes the development of NRE, reduces dependence on fossil fuels, and improves energy efficiency in various sectors, including electricity generation. Through this regulation, Bali is expected to become a carbon-neutral region by 2045, by implementing strategies such as ceasing operations of coal-fired power plants, increasing the capacity of solar PV, geothermal, and biomass power plants, and optimizing the interconnection of the Java–Bali transmission network [2].

Additionally, the Electricity Supply Business Plan (RUPTL) of PT PLN (Persero) for the 2025–2034 period has included plans to increase the capacity of RE-based power plants in Bali. This covers the construction of large-scale solar power plants, battery energy storage systems (BESS), and several other power plants. The RUPTL also emphasizes the importance of integrating the electricity system with other islands through interconnections to ensure supply reliability and to support renewable energy penetration [4].

B. RE Potential in Bali

Bali has great potential of RE resources, particularly solar PV, and geothermal power [2][5]. Solar PV has the best opportunity to be developed due to the availability of high level of solar radiation throughout the year. Meanwhile, geothermal energy can be utilized as a stable source to meet base load requirements [1]. Previous research indicated that combining a RE portfolio with energy storage systems may reduce dependence on fossil fuels while ensuring the reliability of electricity supply [6]. However, there are several major challenges in developing RE in Bali, such as infrastructure readiness, access to funding, and challenges in implementing policies.

C. Energy Mix Optimization

Energy mix optimization is a strategic approach that aims to ensure that energy systems can meet demand in a sustainable, reliable, and efficient manner [7][8]. This approach not only focuses on increasing the capacity of RE generation, but also seeks to gradually reduce the use of fossil fuel-based power plants that produce high emissions, such as coal-fired power plants and diesel power plants, which are still in operational within some regions [4].

Interconnection with the Java–Bali transmission system provides advantages for Bali Island, in terms of electricity supply security; however, the interconnection system transmits electricity that is largely derived from fossil fuel sources. Therefore, an increase in RE generation capacity in Bali is necessary, accompanied by grid modernization and the implementation of energy storage technology. This is important to achieve clean energy independence [9].

D. LEAP Software

LEAP is a widely used software tool for analyzing energy planning scenarios and their impact on emissions. In Indonesia, LEAP modeling has been used to assess various NZE scenarios for national energy supply. Through this approach, projections of energy demand, power generation capacity, and the contribution of RE can be calculated in detail. Modeling results indicate that scenarios prioritizing RE and gradually phasing out fossil fuel-powered plants can significantly reduce emissions without compromising the reliability of electricity supply [10].

This approach has been proven to be effective at the national level, and can be adopted for energy planning in Bali. By adjusting parameters to local resource potential, energy needs, and the 2045 NZE target, the use of LEAP enables the development of a more targeted energy transition strategy. Analysis results from LEAP can serve as data-driven policy guidelines, supporting the achievement of a clean energy mix, while maintaining the reliability of the regional electricity system.

III. Research Method

This study adopts a simulation-based quantitative approach in energy planning using LEAP software, combined with preliminary data processing techniques using Microsoft Excel to improve the accuracy and validity of the modeling results. LEAP was selected as the primary analysis tool due to its ability to present a scenario-based approach, which is highly relevant in developing energy transition strategies toward NZE targets. LEAP's flexibility in integrating complex variables such as energy demand projections, power generation capacity, and emission intensity makes it an ideal tool for this study.

This research was conducted for a 20-year timeframe (2025–2045), with the Bali Island as the primary study area. The selection of this period was based on long-term considerations in achieving the 2045 NZE target while ensuring consistency between local and national energy policies.

A. Simulation Scenarios

Three main scenarios were designed to illustrate the various energy policy options that could be implemented in Bali Island. Each scenario reflects a different approach to energy mix management and development, providing a comprehensive picture of the possible impacts and outcomes.

1) Optimistic Scenario

This scenario assumes accelerated progress in the energy transition process, the gradual phase-out of fossil fuel-fired power plants such as coal-fired power plants and diesel-fired power plants, in addition to a significant increase in the use of RE generating systems, including solar PV plants and geothermal power plants.

2) Moderate Scenario

The moderate scenario is reflecting current policies, with a relatively balanced energy mix between fossil and renewable sources, with a gradual electrification progress.

3) Pessimistic Scenario

This scenario indicates a stagnant condition, where fossil-fueled power plants remain dominant, electrification progresses is minimum, and the implementation of clean energy and energy efficiency is delayed.

Among the three scenarios, the analysis focuses on the optimistic scenario as the primary reference. This scenario aligns most closely with Bali Provincial Government goal in achieving NZE by 2045, while also reflecting a more progressive and sustainable energy policy direction.

B. Data and Assumptions

In this study, historical data on electricity consumption, the existing power plant capacities, and the potential for RE in Bali, are the main data used for the analysis. A preliminary data processing using Microsoft Excel was carried out to ensure that all data used in the modeling was accurate and relevant.

For electricity sales projection, an econometric approach considering several important factors, including Regional Domestic Product (RDP) growth and energy elasticity is applied. Projections for the period of 2025 to 2045 for the optimistic scenario, economic growth is estimated to reach 7.7%. Meanwhile, the moderate scenario estimates a growth of 5.86%, and the pessimistic scenario anticipates a growth of 4.84%. For all three scenarios, an energy elasticity of 1.2 was implemented, based on the response of energy consumption to changes in economic growth for the past ten years.

Currently in Bali Island, there are several installed power plants that were built in previous years and is still active. The existing installed power plant capacity in Bali Island can be seen in Table I. In projecting power generation capacity, assumptions are made based on the additional capacity stated in the Accelerated Renewable Energy Development (ARED) plan of the RUPTL 2025–2035 for Bali Province [11]. The details are presented in the Table II. This plan includes the development of RE based power plant that are expected to meet future energy needs. Additionally, to ensure the availability of energy reserves, assumptions based on the RE potential in Bali was also considered. With this approach, a precise analysis for the required power generation capacity to support future energy demand growth would be achieved.

Additional assumptions were made related to the increased in installed power plant capacity in addition to those stated in the RUPTL, due to insufficient supply for the projection demand. The assumptions for the increase in installed capacity for the optimistic and moderate scenarios can be seen in Table III and Table IV.

TABLE I
CAPACITY OF EXISTING INSTALLED POWER PLANTS IN BALI

Power Plant	Type	Capacity	Unit
PLTDG Pesanggaran	Diesel-Gas	182,00	MW
PLTG 1 dan 2 Pesanggaran	Gas	35,95	MW
PLTG 3 dan 4 Pesanggaran	Gas	79,31	MW
PLTD BOT (B) Pesanggaran	Diesel	50,00	MW
PLTG Ex Grati	Gas	195,28	MW
PLTG Gilimanuk	Gas	130,00	MW
PLTG Pemaron	Gas	80,00	MW
PLTU Celukan Bawang	Coal-fired	380,00	MW
SKTL (Submarine Cable)	Interconnection	340,00	MW
PLTMH Panji Muara Raya	Hydro	1,80	MW

TABLE II
PLANNED ADDITIONAL POWER PLANTS ACCORDING TO THE RUPTL

Additional Power Plant	Type	Capacity	Unit
PLTM Titab	Hydro	1,3	MW
PLTM Jawa-Bali (Kouta) Tersebar 2028	Hydro	1,4	MW
PLTM Jawa-Bali (Kouta) Tersebar 2029	Hydro	0,65	MW
PLTMG Bali	Gas	200	MW
PLTGU Jawa-Bali-2 2027	Gas	450	MW
PLTGU Jawa-Bali-2 2028	Gas	450	MW
PLTGU Jawa-Bali-2 2029	Gas	450	MW
PLTP Bedugul 2028	Geothermal	5	MW
PLTP Bedugul 2030	Geothermal	60	MW
PLTP Bedugul 2033	Geothermal	110	MW
PLTS Bali Timur 2025	Solar PV	50	MWp
PLTS Bali Barat 2025	Solar PV	50	MWp
PLTS Bali (Kuota) III 2026	Solar PV	50	MWp
PLTS Bali (Kuota) Tersebar VII 2026	Solar PV	197,73	MWp
PLTS Bali (Kuota) Tersebar VIII 2027	Solar PV	193,66	MWp
PLTS Bali (Kuota) IX 2033	Solar PV	130	MWp
PLTS Bali (Kuota) V 2034	Solar PV	25	MWp
PLTS Bali (Kuota) VI 2034	Solar PV	25	MWp
PLTSa Bali (Kuota) Tersebar 2033	Waste	19	MW
JBC 2030	Interconnection	2000	MW
BESS Bali (Kuota) Tersebar III 2026	BESS	50	MW

BESS Bali (Kuota) Tersebar VII 2026	BESS	100	MW
BESS Bali (Kuota) Tersebar VIII 2026	BESS	50	MW
BESS Bali (Kuota) Tersebar IX 2033	BESS	100	MW

TABLE III
ADDITIONAL POWER PLANTS OUTSIDE THE RUPTL FOR OPTIMISTIC SCENARIO

Additional Power Plant	Type	Capacity	Unit
New PLTM 2042	Hydro	25	MW
New PLTS 2040	Solar PV	333,33	MWp
New PLTS 2041	Solar PV	555,56	MWp
New PLTS 2042	Solar PV	500	MWp
New PLTS 2043	Solar PV	666,67	MWp
New PLTS 2044	Solar PV	722,22	MWp
New PLTS 2045	Solar PV	5000	MWp
New PLTBm 2042	Biomass	90	MW
New BESS 2040	BESS	300	MW
New BESS 2041	BESS	500	MW
New BESS 2042	BESS	450	MW
New BESS 2043	BESS	600	MW
New BESS 2044	BESS	650	MW
New BESS 2045	BESS	4500	MW

TABLE IV
ADDITIONAL POWER PLANTS OUTSIDE THE RUPTL FOR MODERATE SCENARIO

Additional Power Plant	Type	Capacity	Unit
New PLTM 2045	Hydro	25	MW
New PLTS 2045	Solar PV	1413,33	MWp
New PLTBm 2045	Biomass	90	MW
New BESS 2045	BESS	1272	MW

C. Modeling Process

The model was validated by adjusting the LEAP simulation results to the latest historical data to ensure consistency between the model and actual conditions. After the validation stage, the simulation was carried out to see the impact of each scenario on the followings:

- Electricity consumption
- Power plant capacity
- Energy mix

All LEAP outputs are quantitatively analyzed and presented in the form of graphs, tables, and comparative narratives to highlight differences in results between scenarios, with a focus on optimizing the energy mix toward the 2045 NZE target.

IV. RESULTS AND DISCUSSION

Energy scenario modeling for Bali Island using LEAP software provides a comprehensive projection of various aspects of the energy system, including energy consumption levels, installed power plant capacity, and the proportion of energy sources used. The simulation results for each scenario show different patterns and dynamics of energy transition, reflecting variations in future energy development policies and strategies.

A. Electricity Demand Projection

Electricity consumption is one of the key indicators that determine the direction and needs in planning an area's electrical system. Based on the simulation results, it is projected that the level of electricity consumption in Bali Island will experience a significant increase during the period 2025 to 2045. This upward trend is primarily driven by several key factors, including population growth, which implies an increase in per capita energy demand, the expansion and intensification of economic activities requiring larger energy supplies, and the acceleration of electrification processes in the residential and transportation sectors. The combination of these factors has the potential to accelerate the pace of electricity demand in the future, necessitating adaptive and sustainable energy system management strategies.

Figure 1 shows the electrical energy demand projection of Bali Island for year 2025-2045. The three different scenarios are indicated by different curve colors. All scenarios produce an upward trend in electricity consumption during the period 2025–2045, albeit at different growth rates. In the optimistic scenario, the increase is most significant, rising from about 8,000 GWh in 2025 to more than 47,000 GWh in 2045. This surge is driven by accelerated electrification in the transportation and industrial sectors, as well as the widespread adoption of energy-efficient technologies that enhance efficiency while expanding electricity use.

Meanwhile, the moderate scenario shows an increase from about 7,000 GWh in 2025 to 30,600 GWh in 2045, reflecting more controlled growth as electrification progresses gradually and relatively conservative energy policies are implemented. The pessimistic scenario experiences the lowest growth, from about 7,700 GWh in 2025 to about 24,000 GWh in 2045. The low growth in this scenario is due to the slow pace of electrification, limited supportive policies, and low adoption of clean energy technologies.

The high electricity consumption in the optimistic scenario requires a larger increase in power generation capacity compared to other scenarios, which directly affects the composition of future generating energy mix.

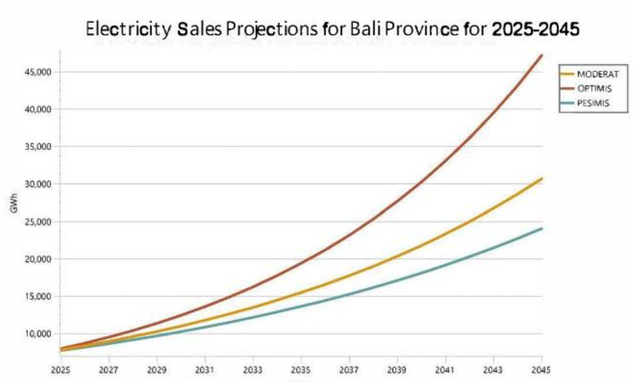

Fig. 1. Electricity Demand Projection of Bali Island for year 2025–2045

B. *Installed Generating Capacity*

Installed power capacity refers to the total capacity of power plants available in the electricity system, including conventional and RE power plants. This figure reflects the maximum ability of a power plant to provide electricity under full operating conditions. In the context of energy planning in Bali Island, installed capacity serves as an important indicator for assessing system reliability, potential power reserves, and infrastructure readiness in the face of increasing electricity demand. Additionally, changes in installed power capacity also reflect energy policy directions, particularly in the transition toward low-emission power plants and reducing dependence on fossil fuels.

Based on the simulation result, the required power plant capacity for optimistic scenario is depicted in Figure 2. This scenario refers to the regional energy development plan (ARED) as outlined in the 2025–2035 PLN Electricity Supply Business Plan (RUPTL) document. Based on this scenario, the power plant capacity is estimated to be sufficient to meet power demand until year 2039. After that, additional capacity is required and the calculation was carried out by optimizing the utilization of RE potential in Bali Island. By the end of year 2045, the total installed capacity is estimated to be 18,903 MW. The composition of power plant is dominated by solar PV power plants, BESS, and Java-Bali interconnection system, as shown in Figure 2.

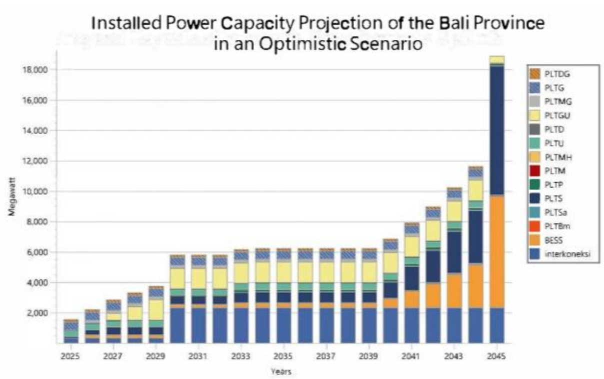

Fig. 2. Simulation result of power plant capacity for Optimistic Scenario

Similarly, the simulation result for moderate scenario indicated that the power plant capacity is sufficient to meet power generation needs until year 2044. In 2045, additional capacity will be required by utilizing the available RE potential in Bali Island. By the end of year 2045, the total installed capacity reaches 7,910 MW. The composition of the power plants includes solar PV, BESS, Java-Bali interconnections, and Combined Cycle Power Plants as depicted in Figure 3.

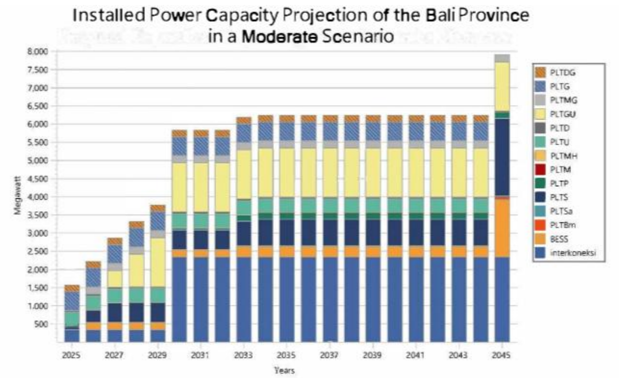

Fig. 3. Simulation result of power plant capacity for Moderate Scenario

For the pessimistic scenario, the additional power plant capacity is based entirely on ARED of the 2025–2035 PLN RUPTL. The simulation results indicated that the power plant capacity is sufficient to meet power needs until 2045, therefore no further additional capacity beyond those stated the document is required. The total installed capacity at the end of year 2045 may reach 5,863 MW, significantly below that of optimistic scenario. The power generating mix is dominated by solar PV, Java-Bali interconnection, combined cycle power plant and natural gas power plants. Figure 4 shows detailed power plant capacity during the period of analysis for pessimistic scenario.

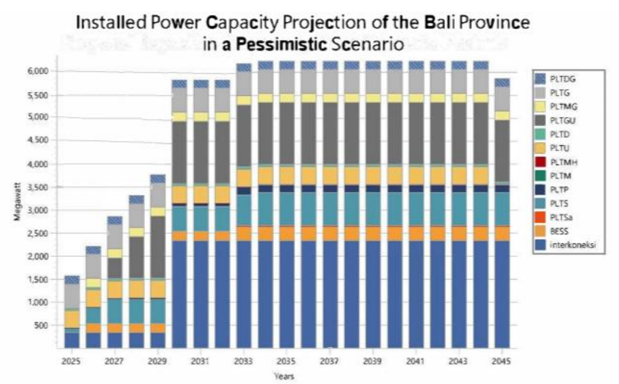

Fig. 4. Simulation result of power plant capacity for Pessimistic Scenario

C. *Energy Mix*

Changes in the composition of the energy mix are a key factor in the success of the energy transition process in Bali Island towards a more environmentally friendly and sustainable energy system. The energy mix from various power plants illustrates the contribution of each energy source to the total generated electricity. This mix is crucial as it reflects the direction of the region's energy policy, particularly in terms of energy supply security, resource efficiency, environmental conservation, and the transition to a low-emission energy system. With an ideal energy mix, the risk of dependence on a single energy source can be minimized, energy system resilience can be strengthened, and long-term operational costs can be effectively reduced.

The optimistic scenario describes an ambitious energy transition approach that is in line with the 2045 NZE target.

From Figure 5, it can be seen that in year 2025, Bali energy mix is still dominated by natural gas with a percentage of 36.9%, followed by coal at 25.5%, diesel at 10.5%, and electricity supply from interconnections outside Bali. In the following years, the contribution of fossil fuel power plants continues to decline, with coal being completely phased out in 2045. RE generation experiences significant growth, particularly in solar PV power plants, which an increase from about 2.4% in 2030 to about 45.9% in 2045. The geothermal energy begins to contribute in 2033 with a stable share of 3.3%, while biomass energy emerges in 2042 and reaches 1.5% by the end of the analysis period. Overall, by 2045, the energy mix from RE sources may reach 51.1%.

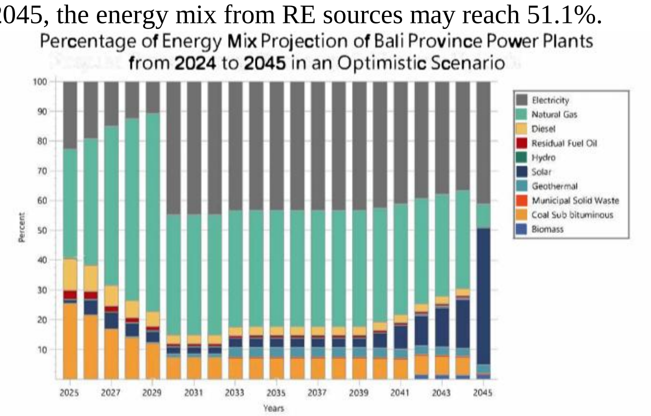

Fig. 5. Energy Mix of Bali in year 2025-2045 for Optimistic Scenario

The moderate scenario describes a gradual energy transition process, taking into account infrastructure limitations, technological readiness, and national policy dynamics. In 2025, coal accounts for 25.5% of the total energy mix, but will gradually decline to 12% in 2029, before being completely phased out in 2045. Meanwhile, natural gas experiences a significant surge, from 36.9% in 2025 to 66.5% in 2029, and then stabilizing at a moderate level. In the first decade, the contribution of RE power plant remains limited; energy from solar PV reaches as low as 2.4% by 2031, while geothermal contributes about 1.3%. The significant acceleration of RE integration begins in 2033, with increased contributions from geothermal and biomass sources. By the end of year 2045, solar power reaches 12.8%, geothermal 3.6%, and biomass 1.9%. Although coal, diesel, and fuel oil are phased out by 2045, the total RE mix only reaches 19.3%, indicating a significant transition, though not as rapid as that in the optimistic scenario. Figure 6 shows the energy mix of Bali Island for the Moderate Scenario.

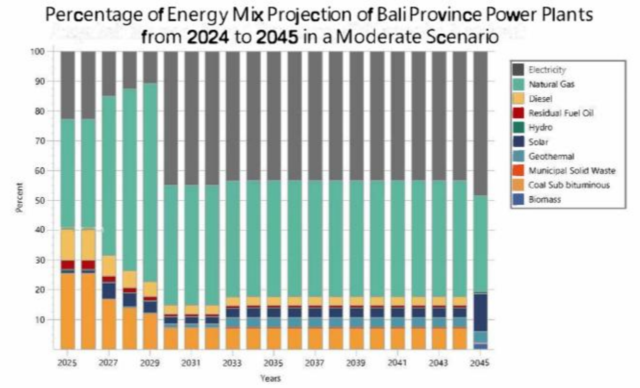

Fig. 6. Energy Mix of Bali in year 2025-2045 for Moderate Scenario

In contrast, the pessimistic scenario reflects a situation in which the adoption of RE is very limited. The power plant capacity growth follows the RUPTL without further additional plants, therefore the proportion of energy mix from fossil fuels power plants remains high until year 2045. In 2025, diesel is the largest contributor with a 44.8% share, followed by Java-Bali interconnection system, and coal fired power plant. Although diesel power plants share declines to 21.2% by 2029, its role remains significantly high until year 2045. Natural gas increases from 2.5% to 50.3% by 2029, but the growth of RE power plant remains very slow. The energy supply form Java-Bali interconnection system dominates from 2030 to 2044 with a 43.4% share, indicating a reliance on external supply. The proportion of RE sources remains low, with solar power reaching about 3.4%, geothermal of about 3.5%, geothermal 0.4%, and hydro of about 0.1%. Note that no contribution from biomass energy in this scenario. By 2045, despite the phase-out of coal and diesel, the energy mix from RE sources may reach 7.4%, a significantly below the national target. Figure 7 depicts the energy mix of Bali Island in year 2025-2045 for Pessimistic Scenario.

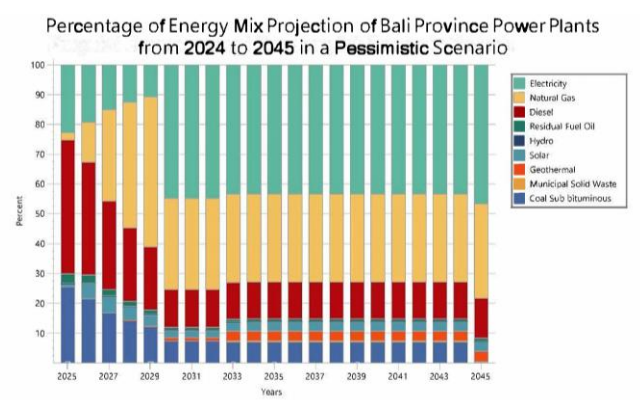

Fig. 7. Energy Mix of Bali in year 2025-2045 for Pessimistic Scenario

V. CONCLUSIONS

This study shows that optimizing the energy mix of power plants is the main strategy for Bali Island to achieve the NZE target by 2045. The optimistic scenario reflects the most progressive transition, where the proportion of the energy mix from RE could reach 51.1% by 2045, accompanied by the complete phase-out of coal, diesel, and fuel oil use. The moderate scenario shows a gradual increase to 19.3%, while the pessimistic scenario experiences stagnation with an RE contribution of only about 7.4%. These differences underscore that achieving the NZE target requires consistent and integrated acceleration measures.

The results of this analysis confirm that the success of the energy transition in Bali is highly dependent on a combination of firm policies, accelerated development of RE infrastructure, strengthened electricity system interconnections, and sustained investment support. Further research in integrating load variability factors, energy storage technology potential, and more detailed economic analysis has been planned to enrich the implementation strategy for a more detailed optimal energy mix.

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