

Projection of Electricity Generation Profiles and Carbon Emissions Towards 2060: The Indonesian Context

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Abstract

Indonesia's electricity sector remains heavily dependent on coal, contributing around 35–40% of national greenhouse gas emissions despite abundant renewable energy potential. This study uses the Long-range Energy Alternatives Planning System (LEAP) to project electricity demand, generation mix, carbon emissions, and capital investment needs in Indonesia until 2060, based on the 2025–2034 Electricity Supply Business Plan (*Rencana Usaha Penyediaan Tenaga Listrik*, RUPTL) as the baseline. The research addresses three questions: (1) the alignment of RUPTL 2025–2034 with the Net Zero Emission (NZE) 2060 target; (2) policy gaps that may hinder NZE achievement; and (3) alternative scenarios to accelerate the energy transition while ensuring reliability and affordability. Both baseline and optimized scenarios are analyzed, covering electricity consumption across household, commercial, and industrial sectors and the evolution of the generation mix. The study integrates emissions modeling with capital cost estimation to provide a comprehensive environmental and economic assessment. Results show that the baseline scenario supports gradual renewable energy integration; however, coal and natural gas remain dominant, resulting in continued emissions growth. Under the optimized scenario, total electricity generation is projected to increase from 275.7 thousand GWh in 2024 to 1,075.4 thousand GWh in 2060, dominated by renewable energy sources such as hydropower, solar PV, wind, biomass, and geothermal energy. Electricity sector emissions initially increase from 26.7 million metric tonnes CO₂ equivalent in 2024 to 39.7 million metric tonnes CO₂ equivalent in 2030, before declining gradually and reaching net zero emissions by 2060 through the complete phase-out of fossil fuel-based power plants. Achieving this transition requires cumulative capital investment of approximately USD 653.4 billion by 2060. This study contributes by evaluating Indonesia's latest electricity planning, identifying structural and policy barriers to NZE 2060, and proposing pathways for faster decarbonization in coal-dependent developing countries. The integrated analysis offers practical guidance for designing financially feasible and sustainable strategies toward a fully decarbonized power sector.

Keywords

Energy modeling, LEAP, Renewable Energy, Energy system, Optimization.

1. Introduction

Indonesia is the fourth most populous country in the world, with an estimated population of approximately 281.6 million as of 2024 and an average annual growth rate of around 1.11% (BPS, 2024). This steady population growth, combined with rapid urbanisation and increasing industrial activity, has resulted in a continuous rise in national energy consumption. As living standards and electrification ratios improve, electricity demand has grown significantly, particularly in the residential, commercial, and industrial sectors. Consequently, the structure and sustainability of Indonesia's energy system have become crucial in supporting long-term economic growth and achieving environmental objectives. Moreover, Indonesia's strong economic performance, driven by the expansion of the manufacturing sector, digital transformation, and infrastructure development, continues to increase energy demand, particularly in Java, Sumatra, and Kalimantan, which serve as the leading industrial hubs. However, this growing energy demand presents a dual challenge: ensuring the availability and reliability of energy supply to sustain economic growth while simultaneously reducing greenhouse gas emissions in line with global climate commitments. Global climate change mitigation has placed the energy sector at the forefront of the transition toward a low-carbon system.

Currently, coal remains the primary source of Indonesia's energy mix, particularly in meeting domestic electricity demand. Approximately 67% of power plants in Indonesia still rely on coal as their fuel source. This indicates that

Indonesia has not yet fully disengaged from, and remains heavily dependent on, coal use, despite the global shift toward renewable energy (Directorate General of Mineral and Coal, 2024). This dependence makes the power sector the largest contributor to national greenhouse gas emissions, accounting for around 35-40% of the total (IESR, 2022). In response, the Government of Indonesia has committed to achieving net zero emissions (NZE) by 2060 or earlier, as stated in the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) and the Enhanced Nationally Determined Contribution (NDC) (Coordinating Ministry for Economic Affairs of the Republic of Indonesia, 2024) (Figure 1).

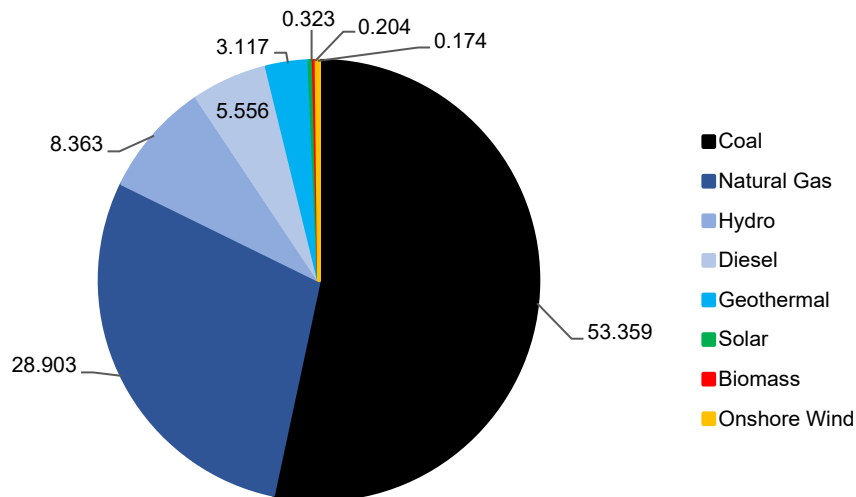


Figure 1. Primary energy share used for electricity generation in 2024
Source: State electricity company of Indonesia (PT. PLN Persero), 2025

1.1 Objectives

Within the framework of energy policy analysis, the Long-range Energy Alternatives Planning System (LEAP) is widely applied to project energy demand and supply, as well as to estimate carbon emissions under different policy scenarios. This study aims to project the development of Indonesia's electricity system through 2060 and to assess the implications for carbon emissions based on the 2025-2034 RUPTL scenario using the LEAP model. Specifically, this research seeks to analyze the consistency of the 2025-2034 RUPTL with Indonesia's decarbonization pathway toward NZE 2060. It aims to address three main questions: (1) to what extent the 2025-2034 RUPTL is consistent with the long-term decarbonization trajectory; (2) what policy gaps remain that could hinder the achievement of NZE 2060; and (3) what alternative scenarios could accelerate the energy transition without compromising the reliability or affordability of electricity supply.

The main contributions of this study are threefold. First, it provides an evidence-based evaluation of the most recent electricity planning policies through a systematic and transparent modeling approach using LEAP. Second, it identifies structural gaps in national energy planning that can serve as the basis for future policy recommendations on the energy transition. Third, it enriches the international literature on energy transition in developing countries with high coal dependency, positioning Indonesia as an important case study in the global discourse on power sector decarbonization pathways.

2. Literature Review

Numerous studies have examined the characteristics and comparative advantages of energy system models. (Prina et al., 2021) reviewed bottom-up energy system models at the island scale and identified LEAP as a comprehensive framework capable of simulating technologies and associated costs across multiple sectors, including electricity, transport, and heating. Similarly, (Ringkjøb et al., 2018) highlighted LEAP's flexibility and wide applicability compared to other energy modelling tools.

Despite the availability of alternative modelling frameworks such as OSeMOSYS and MARKAL, LEAP remains widely applied due to its suitability for long-term scenario analysis and national-scale energy planning. In contrast to optimization-based models like MARKAL, which primarily focus on cost minimization, LEAP offers greater flexibility in representing policy-driven scenarios, although it does not inherently perform endogenous optimization. Several studies have applied LEAP and its extended frameworks to national and regional energy systems. (Gebremeskel et al., 2023) combined OSeMOSYS and LEAP to model Ethiopia's electricity system, demonstrating that improvements in grid efficiency significantly influence future investment decisions. (Wang et al., 2023) applied the LEAP-NEMO framework to identify cost-efficient decarbonization pathways in Inner Mongolia, showing that substantial emission reductions can be achieved at relatively low cost.

In Southeast Asia, (Babatunde et al., 2021) analyzed Malaysia's electricity sector and found that removing fossil fuel subsidies alone is insufficient to reduce CO₂ emissions due to fuel switching effects. (Fernandez et al., 2025) further applied the LEAP-NEMO model to Malaysia, projecting a gradual transition toward renewable energy supported by storage integration and a steady decline in emissions. Other national-level studies further confirm LEAP's relevance for long-term energy planning. (Calikoglu and Aydinalp Koksak, 2023) used LEAP to explore Turkey's net-zero transition, emphasizing the role of nuclear, renewable energy, and CCUS technologies. (Malka et al., 2023) showed that achieving net-zero emissions in Norway requires carbon taxation and CCUS adoption, particularly in the oil and gas sector. In Nepal, (Shakya et al., 2023) demonstrated that net-zero strategies significantly reduce both carbon and black carbon emissions while improving air quality and energy security.

For developing countries, LEAP has also been widely used in long-term decarbonization studies. (Kanugrahan and Hakam, 2023) applied LEAP-NEMO to Indonesia's power sector and highlighted the necessity of coal phase-out and accelerated renewable energy deployment to achieve net-zero emissions by 2060. Similarly, (Akpahou et al., 2024) projected a substantial increase in energy demand and greenhouse gas emissions under a business-as-usual scenario in Benin, emphasizing the importance of policy intervention.

In comparison, optimization-based models such as MARKAL (Ozawa et al., 2022) focus on cost-minimizing pathways and indicate that full decarbonization of the electricity sector is required to achieve carbon neutrality, with strong reliance on renewable energy and carbon removal technologies. Based on this literature, it is evident that although LEAP has been widely used in national energy system modelling, most existing studies focus either on emission pathways or policy scenarios in isolation. Few studies integrate electricity generation profiles, emission trajectories, and long-term transition pathways within a unified framework specifically for Indonesia up to 2060. Therefore, this study positions itself by addressing this gap through the projection of electricity generation profiles and carbon emissions in Indonesia up to 2060 using the LEAP framework, providing a more integrated and policy-relevant assessment of the national energy transition pathway. Based on this review section, LEAP was chosen in comparison to other models based on several criteria. It has a projection range spanning from 20 to 50 years and is well-suited for energy modelling at national geographical coverage. It is characterized as a hybrid or integrated model and offers flexibility to conduct both static and long-term scenario analyses. In addition, it can account for greenhouse gas (GHG) emissions from both energy and non-energy sectors.

3. Methods

3.1 LEAP (Low Emissions Analysis Platform)

LEAP, the Low Emissions Analysis Platform, is a powerful and versatile software system for integrated energy, climate change mitigation and air pollution abatement planning. Developed at SEI US, LEAP continues to evolve and improve to meet the needs of its many users (Stockholm Environment Institute, 2025). In the context of long-term energy planning, LEAP (Long-range Energy Alternatives Planning System) provides a highly adaptable framework for analysing energy demand across different levels of detail, ranging from aggregated national projections to sectoral or end-use-specific analyses (Somerville, MA, 2025).

The modelling process in LEAP consists of two main stages: the accounting stage and the optimisation stage. During the accounting stage, the model estimates future energy demand across all sectors over the study horizon based on input parameters, and subsequently determines the total energy supply required to meet that demand-factoring in system losses and reserve margins. This stage focuses on demand-supply consistency without yet determining specific technology pathways (Masoomi et al., 2022). The optimisation stage, on the other hand, refines the model outcomes by integrating economic and environmental objectives to identify the most cost-effective and sustainable energy mix.

In this study, LEAP is applied to simulate Indonesia's power development pathway and associated carbon emissions, aligning with the national target of achieving Net Zero Emissions by 2060.

3.2 Modelling of Energy Supply and Transformation

This study utilized a combination of national and international datasets to construct a comprehensive LEAP-based model for projecting Indonesia's power system development and associated carbon emissions toward the Net Zero Emission (NZE) 2060 target. The primary data were obtained from PT PLN (Persero), particularly the *Rencana Usaha Penyediaan Tenaga Listrik* (RUPTL) 2025-2034 and the PLN Statistics 2024 (Operational Data, Unaudited). The RUPTL document provides critical parameters such as installed generation capacity, electricity production, renewable energy potential, demand forecasts, and national energy targets. Meanwhile, the PLN Statistics report offers detailed operational data, including customer categories, average annual electricity sales, and generation performance across power plant types. In addition, complementary data and references were sourced from the Ministry of Energy and Mineral Resources (ESDM), the Institute for Essential Services Reform (IESR), and the U.S. Energy Information Administration (EIA). These sources supply essential information on national energy policy frameworks, renewable energy development indicators, and international electricity benchmarks. All datasets were integrated and harmonized within the LEAP framework to model Indonesia's electricity demand, generation mix, and carbon emission trajectories under different policy scenarios, providing a robust analytical basis for assessing the country's pathway toward NZE 2060. Figure 2. illustrates the methodology process flowchart of the development of alternative LEAP models for Indonesia towards 2060.

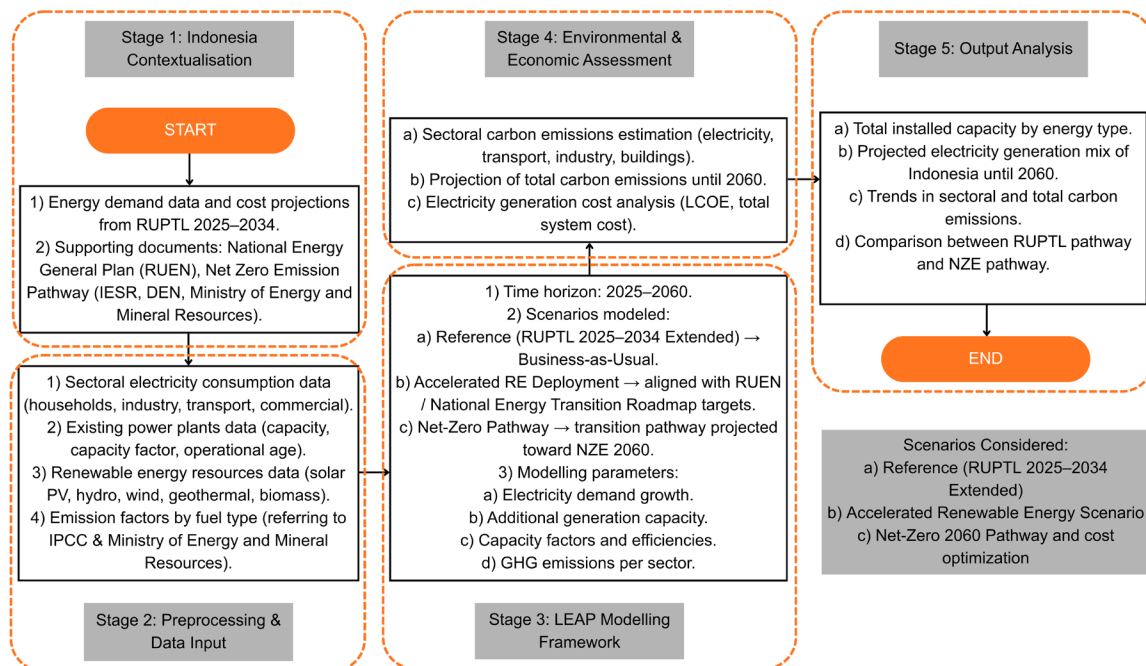


Figure 2. Methodology Stages of LEAP Model Development

4. Data Collection

The data used in this study were collected from a combination of official planning documents, statistical reports, and technical databases related to Indonesia's energy and electricity sector. Electricity demand data were compiled for major consuming sectors, including households, industry, transportation, and commercial buildings, based primarily on the 2025-2034 RUPTL and national energy statistics. Information on existing power plants such as installed capacity, capacity factors, operational age, and generation technology was obtained from PLN reports and the Ministry of Energy and Mineral Resources. To represent future supply options, data on renewable energy resources, including solar PV, hydropower, wind, geothermal, and biomass potentials, were gathered from the National Energy General Plan (RUEN) and other government publications. Emission factors for each fuel type were adopted from IPCC guidelines and national inventories to ensure consistency with international accounting standards. Cost projections for

generation technologies, fuel prices, and demand growth assumptions were also incorporated as key inputs for the LEAP model. All datasets were harmonized and validated prior to modelling to ensure reliability and comparability across scenarios.

5. Results and Discussion

5.1 Numerical Results

The results of the LEAP model provide a detailed projection of electricity demand across different sectors in Indonesia. Table 1 presents the energy demand composition for the years 2024, 2034, and 2060 under the studied scenarios. The table highlights the growth trends and shifts in the demand share among households, industry, commercial, social, government buildings, public lighting, and other sectors, providing insight into how energy consumption patterns are expected to evolve over time.

Table 1. Demand Sector Condition

Demand	2024		2034		2060	
	Number (thousand GWh)	%	Number (thousand GWh)	%	Number (thousand GWh)	%
Household	130.4	42.59	141.9	33.02	173.6	13.88
Industry	92.2	30.11	138.9	32.32	402.7	32.19
Commercial	58.8	19.2	107.9	25.1	522.8	41.79
Social	12.7	4.15	21	4.89	77.6	6.2
Gov. Building	5.4	1.76	9	2.09	33.1	2.65
Public Lighting	3.5	1.14	5.8	1.35	21.6	1.73
Others (T.C.L.)	3.2	1.05	5.3	1.23	19.6	1.57
Total	306.2	100	429.8	100	1,251	100

The results indicate that industrial and household sectors remain the dominant electricity consumers throughout the projection period, although their relative shares change significantly over time. In 2024, the household sector accounted for the largest share at 42.59% (130.4 thousand GWh), followed by the industrial sector at 30.11% (92.2 thousand GWh) and the commercial sector at 19.2% (58.8 thousand GWh). By 2034, the household sector is expected to continue slightly exceeding industrial consumption, accounting for 33.02% (141.9 thousand GWh) compared to 32.32% (138.9 thousand GWh). However, the industrial sector is projected to surpass household demand in subsequent years, driven by rapid industrialization, energy-intensive manufacturing, and the expansion of industrial estates. By 2060, industrial demand becomes the dominant component, accounting for 32.19% (402.7 thousand GWh) of total consumption, while the household share declines to 13.88% (173.6 thousand GWh) due to improvements in appliance efficiency and saturation effects. The commercial sector expands significantly to 522.8 thousand GWh (41.79%), reflecting the growth of service-oriented and digital-based economies. Other sectors, such as social, government buildings, public lighting, and others, contribute modest but gradually increasing shares. Overall, total electricity demand is expected to increase from 306.2 thousand GWh in 2024 to 1,251 thousand GWh in 2060.

5.2 Graphical Results

The final energy demand in Indonesia is projected to increase continuously from 316.1 thousand GWh in 2025 to 1,254.0 thousand GWh in 2060. The household sector remains one of the major contributors to electricity consumption, with demand rising gradually from 131.5 thousand GWh in 2025 to 176.6 thousand GWh in 2060. This growth reflects the increasing number of households, population growth, urbanization, and wider access to electricity services. The industrial sector shows a more rapid increase in electricity demand, growing from 96.0 thousand GWh in 2025 to 402.7 thousand GWh in 2060. The increase is associated with industrial expansion, higher manufacturing activities, and the growing adoption of electrically driven industrial processes. Electricity demand in the business sector experiences the highest growth among all sectors, increasing from 62.4 thousand GWh in 2025 to 522.8 thousand GWh in 2060. The growth is influenced by the expansion of commercial buildings, retail activities, offices, hotels, and other service-related sectors that require higher electricity consumption. The social sector also shows a steady increase, from 13.3 thousand GWh in 2025 to 77.6 thousand GWh in 2060, reflecting the growing electricity needs of educational institutions, healthcare facilities, and other public service infrastructures. In the government sector, electricity demand rises from 5.7 thousand GWh in 2025 to 33.1 thousand GWh in 2060 as administrative

activities and public facilities continue to expand. Public street lighting (PJU) demand increases from 3.7 thousand GWh in 2025 to 21.6 thousand GWh in 2060, indicating the continued development of urban infrastructure and public lighting systems. Meanwhile, electricity demand in the other TCL category grows from 3.4 thousand GWh in 2025 to 19.6 thousand GWh in 2060, following the increasing utilization of electricity in various supporting activities and smaller-scale sectors (Figure 3).

Energy Demand Forecasting by Sector

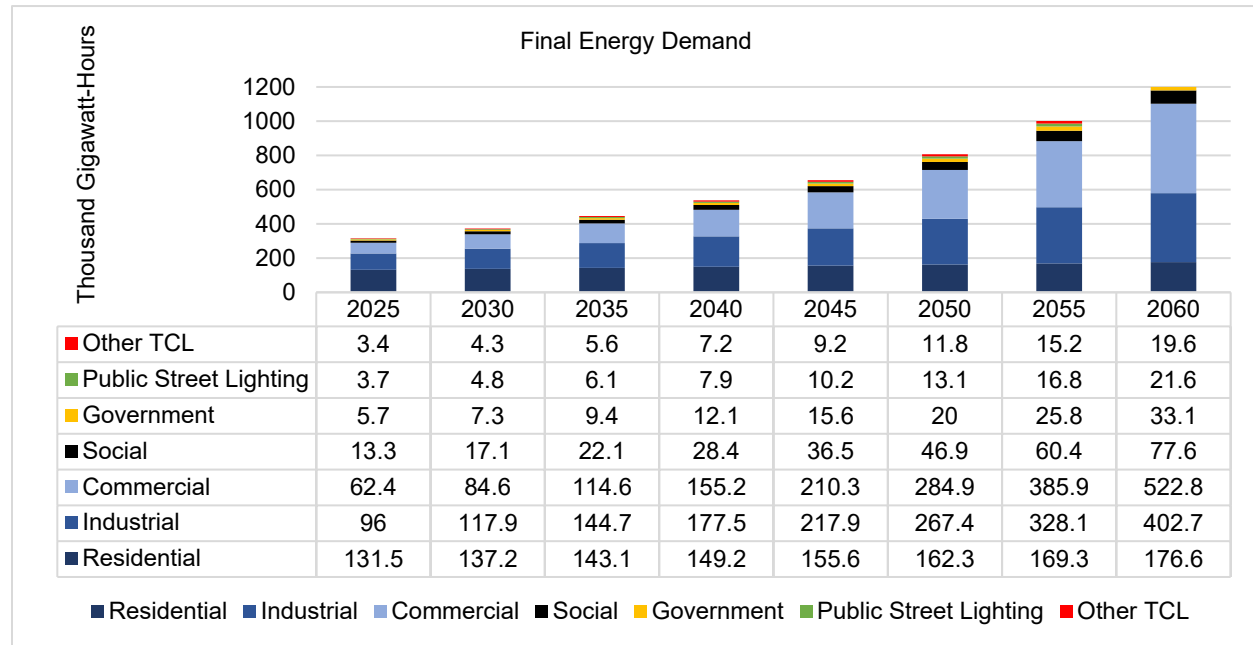


Figure 3. Energy Demand Forecasting by Sector

Energy Supply Sector Condition

Figures 4 illustrates the projected dynamics of Indonesia's power generation capacity expansion and retirement over the 2025–2060 period. As shown in Figure 4(a), the capacity additions are dominated by renewable energy technologies, particularly hydropower plants (*Pembangkit Listrik Tenaga Air*, PLTA), mini-hydropower plants (*Pembangkit Listrik Tenaga Minihidro*, PLTM), micro-hydropower plants (*Pembangkit Listrik Tenaga Mikrohidro*, PLTMH), pumped-storage hydropower plants (*Pembangkit Listrik Tenaga Air Pumped Storage*, PLTA PS), run-of-river hydropower plants (*Pembangkit Listrik Tenaga Air Laut*, PLTAL), geothermal power plants (*Pembangkit Listrik Tenaga Panas Bumi*, PLTP), wind power plants (*Pembangkit Listrik Tenaga Bayu*, PLTB), solar photovoltaic power plants (*Pembangkit Listrik Tenaga Surya*, PLTS), and solar photovoltaic–battery energy storage systems (*Pembangkit Listrik Tenaga Surya–Battery Energy Storage System*, PLTS-BESS). Battery energy storage systems (Battery Energy Storage System, BESS) also exhibit increasing deployment to support grid stability and renewable energy integration. Biomass power plants (*Pembangkit Listrik Tenaga Biomassa*, PLTBM), biogas power plants (*Pembangkit Listrik Tenaga Biogas*, PLTBg), and waste-to-energy power plants (*Pembangkit Listrik Tenaga Sampah*, PLTSa) further contribute to the diversification of Indonesia's future low-carbon electricity mix.

Conversely, Figure 4(b) illustrates the gradual retirement of fossil-fuel-based power plants, including gas turbine power plants (*Pembangkit Listrik Tenaga Gas*, PLTG), gas engine power plants (*Pembangkit Listrik Tenaga Mesin Gas*, PLTMG), combined-cycle gas turbine power plants (*Pembangkit Listrik Tenaga Gas dan Uap*, PLTGU), diesel power plants (*Pembangkit Listrik Tenaga Diesel*, PLTD), and coal-fired steam power plants (*Pembangkit Listrik Tenaga Uap*, PLTU). The retirement trend intensifies after 2040, in line with Indonesia's Net Zero Emission (NZE) 2060 roadmap and the accelerated deployment of renewable and low-carbon technologies. By 2060, the total retired fossil-based generation capacity is projected to exceed 3 GW, indicating a significant structural transformation within Indonesia's national electricity system (Figure 5 and 6).

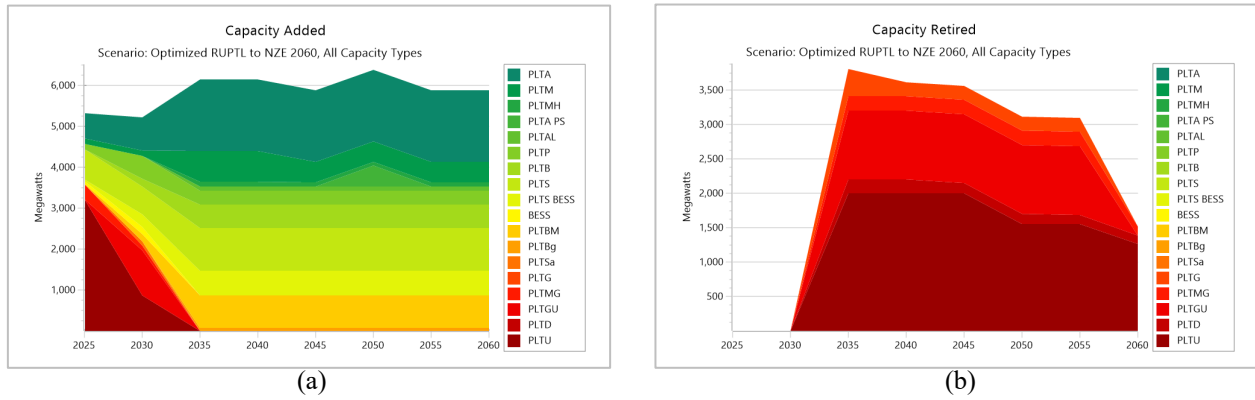


Figure 4. Energy Supply Sector Condition (a) Capacity Added and (b) Capacity Retired)

Electricity Generations by Power Plant

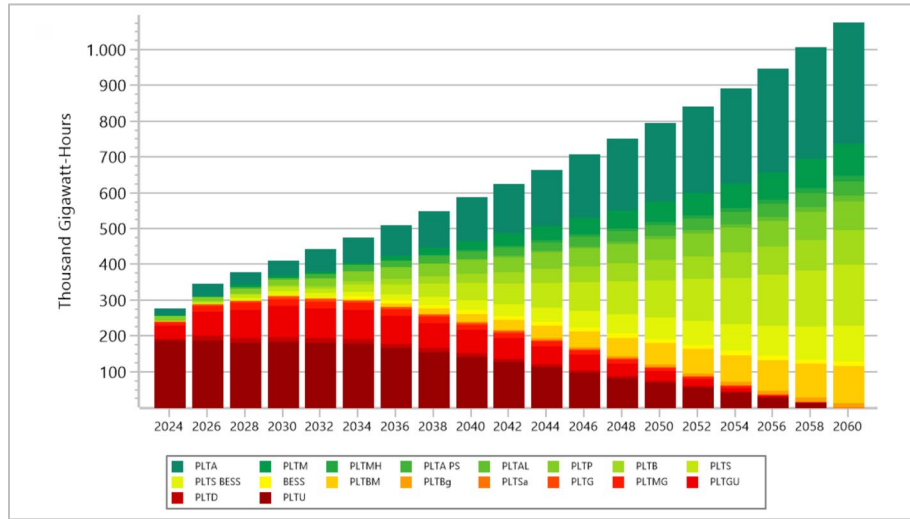


Figure 5. Electricity Generations by Power Plant

Table 2. Electricity Generations by Power Plant

Power Plant Type	2024	2030	2036	2042	2048	2054	2060	Total
PLTA	15,8	38,3	83,8	136,5	197,4	262,3	336,6	2.869,7
PLTM	1,5	6,9	13,0	34,0	51,0	69,2	90,1	697,0
PLTMH	0,1	0,2	1,2	4,4	7,6	11,1	15,1	103,1
PLTA PS	0	4,6	18,0	23,9	28,2	35,1	40,2	416,0
PLTAL	0	0,2	1,0	3,8	7,0	10,5	14,5	95,5
PLTP	13,9	15,4	31,5	42,2	54,6	67,5	82,3	822,2
PLTB	0,4	4,8	14,8	31,5	50,7	71,4	95,1	705,5
PLTS	0,4	12,2	28,8	58,2	92,2	128,8	170,7	1.291,8
PLTS BESS	0	8,5	15,7	33,1	53,2	74,9	99,6	747,8
BESS	0	4,1	10,5	11,2	12,0	12,7	13,6	177,1
PLTBM	1,7	2,2	8,3	28,1	51,0	75,9	104,3	697,5
PLTBg	0	0,1	0,8	2,9	5,3	7,9	10,9	71,4
PLTSa	0	1,9	1,9	2,1	2,2	2,3	2,5	35,2
PLTG	2,8	6,3	5,2	3,5	2,2	0,8	0	60,2

PLTMG	7,9	19,1	18,3	14,6	10,4	5,3	0	227,3
PLTGU	38,2	87,3	76,3	57,2	35,3	9,5	0	890,3
PLTD	3,4	14,3	12,4	9,1	6,3	3,1	0	155,1
PLTU	189,6	183,5	168,4	129,1	84,0	43,7	0	2.215,9
Total	275,7	409,8	510,0	625,4	750,6	89,2	1.075,4	12.278,4

The Electricity Generation by Power Plant table (Table 2) presents the projected electricity generation based on power plant types during the 2024–2060 period, with the unit expressed in thousand gigawatt-hours (thousand GWh). Based on the projection results, total national electricity generation increases significantly from 275.7 thousand GWh in 2024 to 409.8 thousand GWh in 2030. Furthermore, total electricity generation continues to rise to 510.0 thousand GWh in 2036, 625.4 thousand GWh in 2042, 750.6 thousand GWh in 2048, 892.2 thousand GWh in 2054, and reaches 1,075.4 thousand GWh in 2060. Cumulatively, the total electricity generation during the projection period reaches 12,278.4 thousand GWh. Coal-fired power plants (PLTU) remain the largest contributor at the beginning of the projection period, generating 189.6 thousand GWh in 2024. However, electricity generation from PLTU gradually declines to 183.5 thousand GWh in 2030, 168.4 thousand GWh in 2036, 129.1 thousand GWh in 2042, 84.0 thousand GWh in 2048, and 43.7 thousand GWh in 2054 before completely ceasing operation by 2060. Cumulatively, total electricity generation from PLTU reaches 2,215.9 thousand GWh.

On the other hand, renewable energy power plants show a very significant increase. Hydropower plants (PLTA) increase from 15.8 thousand GWh in 2024 to 38.3 thousand GWh in 2030 and continue to rise until reaching 336.6 thousand GWh in 2060, with a cumulative total of 2,869.7 thousand GWh. Solar power plants (PLTS) also experience rapid growth, increasing from 0.4 thousand GWh in 2024 to 12.2 thousand GWh in 2030, 58.2 thousand GWh in 2042, 128.8 thousand GWh in 2054, and 170.7 thousand GWh in 2060. The cumulative electricity generation from PLTS reaches 1,291.8 thousand GWh. Other renewable energy power plants also experience gradual growth. Geothermal power plants (PLTP) increase from 13.9 thousand GWh in 2024 to 82.3 thousand GWh in 2060, with a cumulative total of 822.2 thousand GWh. Wind power plants (PLTB) increase from 0.4 thousand GWh to 95.1 thousand GWh, with a cumulative total of 705.5 thousand GWh. In addition, biomass power plants (PLTBM) rise from 1.7 thousand GWh in 2024 to 104.3 thousand GWh in 2060, with a cumulative total of 697.5 thousand GWh. Mini-hydro (PLTM) and micro-hydro (PLTMH) power plants also increase gradually, reaching 90.1 thousand GWh and 15.1 thousand GWh respectively by 2060. Energy storage technologies also demonstrate significant development. Solar power plants integrated with battery energy storage systems (PLTS BESS) increase from 8.5 thousand GWh in 2030 to 99.6 thousand GWh in 2060, with a cumulative total of 747.8 thousand GWh. Battery Energy Storage Systems (BESS) increase from 4.1 thousand GWh in 2030 to 13.6 thousand GWh in 2060. In addition, pumped storage hydropower plants (PLTA PS) increase from 4.6 thousand GWh in 2030 to 40.2 thousand GWh in 2060.

Conversely, fossil fuel-based power plants such as PLTG, PLTMG, PLTGU, and PLTD gradually decline toward 2060. Combined cycle gas turbine power plants (PLTGU) decrease from 38.2 thousand GWh in 2024 to 9.5 thousand GWh in 2054 and completely cease operation by 2060. Similar declines also occur in PLTMG, PLTG, and PLTD.

Electricity Generations by Fuel

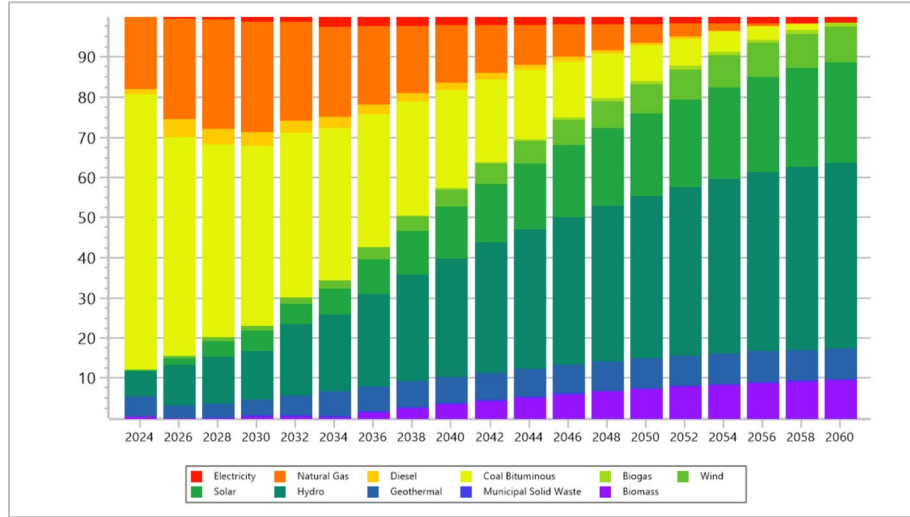


Figure 6. Electricity Generations by Fuel

Table 3. Electricity Generations by Fuel

Fuel	2024	2030	2036	2042	2048	2054	2060
Electricity	0	1,01	2,05	1,79	1,60	1,43	1,26
Natural Gas	17,74	27,51	19,59	12,04	6,38	1,75	0
Diesel	1,22	3,49	2,44	1,45	0,84	0,35	0
Coal Bituminous	68,77	44,76	33,03	20,64	11,19	4,90	0
Biogas	0	0,02	0,15	0,46	0,70	0,88	1,01
Wind	0,15	1,16	2,90	5,03	6,75	8,01	8,85
Solar	0,13	5,06	8,73	14,61	19,37	22,83	25,13
Hydro	6,34	12,23	22,94	32,41	38,80	43,52	46,17
Geothermal	5,03	3,76	6,18	6,75	7,27	7,56	7,65
Municipal Solid Waste	0	0,47	0,38	0,33	0,29	0,26	0,23
Biomass	0,61	0,53	1,62	4,50	6,79	8,51	9,70
total (%)	100,00	100,00	100,00	100,00	100,00	100,00	100,00

The Electricity Generation by Fuel table presents (Table 3) the projected share of electricity generation based on fuel type during the 2024–2060 period, expressed in Thousand Gigawatt-Hours (Thousand GWh). The results indicate a significant transformation in the national electricity mix from fossil fuel dominance toward renewable energy sources. Throughout the projection period, the contribution of renewable energy sources continues to increase, while fossil fuel utilization gradually declines until it is fully phased out by 2060.

Coal bituminous remains the dominant fuel in 2024, accounting for 68.77% of total electricity generation. However, its contribution continuously declines to 44.76% in 2030, 33.03% in 2036, 20.64% in 2042, 11.19% in 2048, and 4.90% in 2054 before reaching zero by 2060. A similar trend is observed for natural gas, which initially contributes 17.74% in 2024 and temporarily increases to 27.51% in 2030 before declining gradually to 19.59% in 2036, 12.04% in 2042, 6.38% in 2048, and 1.75% in 2054, eventually reaching zero in 2060. Diesel also experiences a gradual reduction from 1.22% in 2024 to 0.35% in 2054 before being completely eliminated by 2060.

In contrast, renewable energy sources experience substantial growth throughout the projection period. Hydropower becomes one of the largest contributors among renewable sources, increasing from 6.34% in 2024 to 12.23% in 2030, 22.94% in 2036, 32.41% in 2042, 38.80% in 2048, 43.52% in 2054, and reaching 46.17% in 2060. Solar energy also demonstrates rapid growth, rising from only 0.13% in 2024 to 5.06% in 2030, 14.61% in 2042, 22.83% in 2054, and

25.13% in 2060. This trend highlights the increasing role of solar power as a major contributor to future electricity generation.

Wind energy also increases significantly from 0.15% in 2024 to 8.85% in 2060. Biomass grows from 0.61% in 2024 to 9.70% in 2060, while biogas increases gradually from nearly zero contribution in 2024 to 1.01% by 2060. Geothermal energy remains relatively stable throughout the projection period, contributing between 3.76% and 7.65%. Municipal solid waste contributes a relatively small portion, ranging from 0.47% in 2030 to 0.23% in 2060. In addition, electricity imports or external electricity contributions appear starting in 2030 at 1.01% and gradually decrease to 1.26% by 2060.

Emissions from Electricity Generation

Figure 7 presents the projected carbon emissions from Indonesia's electricity generation sector, categorized by fuel type: coal, diesel, and natural gas, for the period 2024 to 2060. The results show a consistent decline in total emissions, from around 17 million tonnes of CO₂ in 2024 to nearly zero by 2060. At the beginning of the projection period, coal-fired power plants (PLTU) are the primary contributors to emissions, followed by natural gas and diesel units. The continued dominance of coal until approximately 2035 reflects the inertia of existing power infrastructure and the country's dependence on fossil-based baseload generation. After 2040, emissions begin to decrease rapidly as renewable energy capacity expands and coal power plants are gradually phased out. By 2055, the contribution of coal and diesel is expected to become almost negligible, with only a small share of emissions remaining from natural gas, which will continue to serve as a balancing source for the system. This declining trend highlights Indonesia's progress toward a low-carbon power sector consistent with the Net Zero Emission 2060 roadmap. The results underscore the importance of accelerating the retirement of fossil assets, expanding renewable energy generation, and improving energy efficiency to achieve deep emission reductions in the long term.

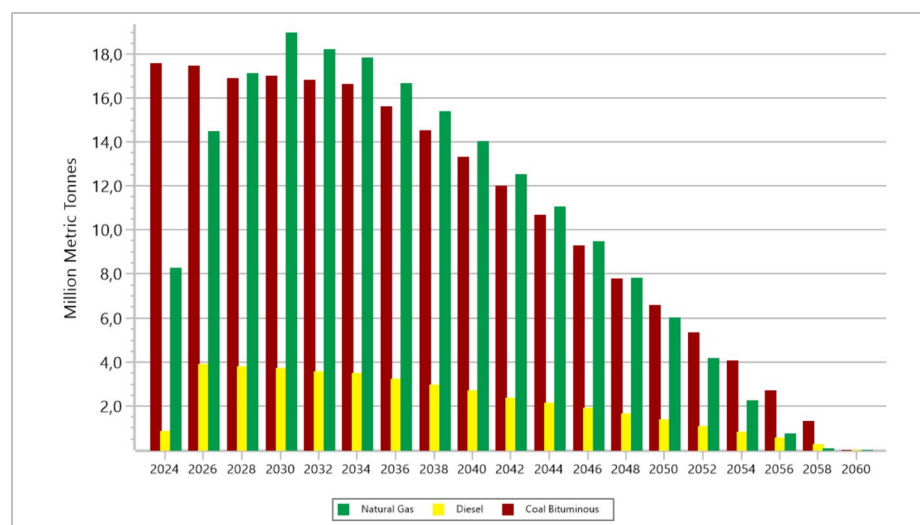


Figure 7. Emissions from Electricity Generation

Table 4. Emissions from Electricity Generation

Fuel	2024	2030	2036	2042	2048	2054	2060	Total
Natural Gas	8,3	19,0	16,6	12,5	7,8	2,3	0	194,8
Diesel	0,9	3,7	3,2	2,4	1,7	0,8	0	40,5
Coal Bituminous	17,6	17,0	15,6	12,0	7,8	4,0	0	205,3
Total	26,7	39,7	35,5	26,8	17,2	7,1	0	440,6

The Emissions from Electricity Generation table (Table 4) presents the projected carbon dioxide equivalent (CO₂e) emissions generated from the electricity generation sector during the 2024–2060 period, expressed in Million Metric

Tonnes CO₂ Equivalent. The projection results indicate that total emissions from the electricity sector gradually decline in line with the reduced use of fossil fuels and the increasing utilization of renewable energy in the power generation system.

In 2024, total emissions from electricity generation reached 26.7 million metric tonnes CO₂ equivalent. These emissions increased to 39.7 million metric tonnes CO₂ equivalent in 2030 due to the still high utilization of fossil fuels, particularly natural gas and coal. However, after 2030, total emissions gradually decreased to 35.5 million metric tonnes CO₂ equivalent in 2036, 26.8 million metric tonnes CO₂ equivalent in 2042, 17.2 million metric tonnes CO₂ equivalent in 2048, and 7.1 million metric tonnes CO₂ equivalent in 2054 before eventually reaching zero in 2060. Cumulatively, total emissions during the projection period reached 440.6 million metric tonnes CO₂ equivalent.

Bituminous coal became the largest source of emissions throughout the projection period. Emissions from coal-based power plants reached 17.6 million metric tonnes CO₂ equivalent in 2024 and slightly decreased to 17.0 million metric tonnes CO₂ equivalent in 2030. Subsequently, emissions continued to decline to 15.6 million metric tonnes CO₂ equivalent in 2036, 12.0 million metric tonnes CO₂ equivalent in 2042, 7.8 million metric tonnes CO₂ equivalent in 2048, and 4.0 million metric tonnes CO₂ equivalent in 2054 before reaching zero in 2060. The cumulative emissions from coal reached 205.3 million metric tonnes CO₂ equivalent.

Natural gas also contributed significantly to emissions. Emissions from natural gas increased from 8.3 million metric tonnes CO₂ equivalent in 2024 to 19.0 million metric tonnes CO₂ equivalent in 2030. Afterward, emissions gradually declined to 16.6 million metric tonnes CO₂ equivalent in 2036, 12.5 million metric tonnes CO₂ equivalent in 2042, 7.8 million metric tonnes CO₂ equivalent in 2048, and 2.3 million metric tonnes CO₂ equivalent in 2054 before eventually reaching zero in 2060. Cumulatively, emissions from natural gas reached 194.8 million metric tonnes CO₂ equivalent. Meanwhile, emissions from diesel were the smallest compared to other fossil fuels. Diesel emissions increased from 0.9 million metric tonnes CO₂ equivalent in 2024 to 3.7 million metric tonnes CO₂ equivalent in 2030, then gradually decreased to 3.2 million metric tonnes CO₂ equivalent in 2036, 2.4 million metric tonnes CO₂ equivalent in 2042, 1.7 million metric tonnes CO₂ equivalent in 2048, and 0.8 million metric tonnes CO₂ equivalent in 2054 before reaching zero in 2060. The cumulative emissions from diesel reached 40.5 million metric tonnes CO₂ equivalent.

Capital Cost of Power Plants

The cumulative capital cost of Indonesia's power plant investments under the Net Zero Emission (NZE) 2060 scenario shows a consistent upward trend, with total expenditure projected to reach nearly USD 650 billion by 2060. This escalation highlights the substantial financial requirements for deploying renewable energy technologies to meet growing electricity demand while phasing out fossil-based generation.

Investment patterns reveal a dominant shift toward hydropower, solar PV, and wind power, especially beyond 2040, reflecting the nation's accelerating transition toward low-carbon energy systems. During the early projection years, coal and gas plants still account for a meaningful share of capital outlays due to ongoing infrastructure expansion and grid reliability needs. Over time, however, their contribution diminishes as renewables gain economic competitiveness, driven by declining capital and operational costs. Overall, the findings emphasize that realizing Indonesia's long-term decarbonization ambitions will demand substantial and sustained financial commitments. Strengthening investment frameworks, fiscal incentives, and financing mechanisms will be essential to mobilize both private and international capital in support of a just and sustainable energy transition (Figure 8).

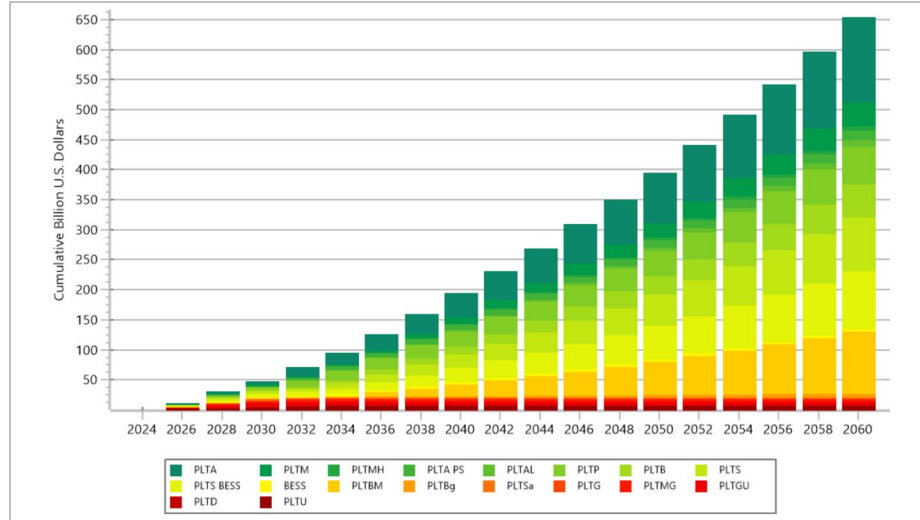


Figure 8. Capital Cost of Power Plants

Table 5. Capital Cost of Power Plants

Power Plant Type	2024	2030	2036	2042	2048	2054	2060
PLTA	0	4,6	24,8	47,1	73,2	103,7	139,4
PLTM	0	1,8	4,7	14,3	21,7	30,5	40,7
PLTMH	0	0	0,5	1,9	3,4	5,2	7,2
PLTA PS	0	1,6	7,3	9,5	10,7	13,8	15,5
PLTAL	0	0,1	0,7	2,6	4,9	7,6	10,7
PLTP	0	4,7	19,6	28,2	38,2	50,0	63,7
PLTB	0	1,8	7,3	16,3	26,8	39,2	53,6
PLTS	0	4,6	13,3	28,4	46,1	66,7	90,8
PLTS BESS	0	6,4	13,3	29,4	48,3	70,3	96,1
BESS	0	1,4	4,1	4,1	4,1	4,1	4,1
PLTBM	0	1,2	6,9	25,6	47,5	73,1	103,0
PLTBg	0	0,0	0,4	1,4	2,7	4,2	5,9
PLTSa	0	2,4	2,6	2,6	2,6	2,6	2,6
PLTG	0	1,2	1,2	1,2	1,2	1,2	1,2
PLTMG	0	3,3	4,0	4,0	4,0	4,0	4,0
PLTGU	0	7,1	7,1	7,1	7,1	7,1	7,1
PLTD	0	0,0	0,0	0,0	0,0	0,0	0,0
PLTU	0	5,2	8,0	8,0	8,0	8,0	8,0
Total	0	47,5	125,7	231,7	350,5	490,9	653,4

The Capital Cost of Power Plants table (Table 5) presents the projected cumulative investment costs for power plant development during the 2024–2060 period, expressed in Real 2020 Cumulative Billion U.S. Dollars. The projection results indicate a substantial increase in investment requirements as the electricity system transitions from fossil fuel-based generation toward renewable energy technologies and energy storage systems. Total cumulative capital costs increase from zero in 2024 to 47.5 billion U.S. dollars in 2030, 125.7 billion U.S. dollars in 2036, 231.7 billion U.S. dollars in 2042, 350.5 billion U.S. dollars in 2048, 490.9 billion U.S. dollars in 2054, and reach 653.4 billion U.S. dollars by 2060. Overall, the cumulative investment throughout the projection period reaches 5,014.7 billion U.S.

dollars. Hydropower plants (PLTA) require the largest cumulative investment among all technologies. Investment in PLTA increases from 4.6 billion U.S. dollars in 2030 to 24.8 billion U.S. dollars in 2036, 47.1 billion U.S. dollars in 2042, 73.2 billion U.S. dollars in 2048, 103.7 billion U.S. dollars in 2054, and reaches 139.4 billion U.S. dollars in 2060. The total cumulative investment for PLTA reaches 1,037.8 billion U.S. dollars.

Solar power plants integrated with battery energy storage systems (PLTS BESS) also require significant investment. Capital costs increase from 6.4 billion U.S. dollars in 2030 to 13.3 billion U.S. dollars in 2036, 29.4 billion U.S. dollars in 2042, 48.3 billion U.S. dollars in 2048, 70.3 billion U.S. dollars in 2054, and 96.1 billion U.S. dollars in 2060. The cumulative investment for PLTS BESS reaches 687.2 billion U.S. dollars. In addition, standalone solar power plants (PLTS) increase from 4.6 billion U.S. dollars in 2030 to 90.8 billion U.S. dollars in 2060, with a cumulative total of 652.1 billion U.S. dollars.

Other renewable energy technologies also experience substantial investment growth. Biomass power plants (PLTBM) increase from 1.2 billion U.S. dollars in 2030 to 103.0 billion U.S. dollars in 2060, with cumulative costs reaching 659.1 billion U.S. dollars. Geothermal power plants (PLTP) rise from 4.7 billion U.S. dollars in 2030 to 63.7 billion U.S. dollars in 2060, with cumulative investment reaching 549.9 billion U.S. dollars. Wind power plants (PLTB) increase from 1.8 billion U.S. dollars in 2030 to 53.6 billion U.S. dollars in 2060, with cumulative costs of 378.2 billion U.S. dollars. Mini-hydro (PLTM) and micro-hydro (PLTMH) power plants also show continuous growth, reaching cumulative investments of 296.1 billion U.S. dollars and 46.9 billion U.S. dollars, respectively.

Energy storage technologies also contribute significantly to overall investment requirements. Standalone Battery Energy Storage Systems (BESS) maintain cumulative investment values around 4.1 billion U.S. dollars from 2036 onward, reaching a cumulative total of 61.3 billion U.S. dollars. Pumped storage hydropower plants (PLTA PS) increase steadily from 1.6 billion U.S. dollars in 2030 to 15.5 billion U.S. dollars in 2060, with cumulative costs reaching 162.2 billion U.S. dollars.

Meanwhile, fossil fuel-based technologies require relatively smaller investments compared to renewable energy technologies. Investments in PLTGU remain constant at 7.1 billion U.S. dollars from 2030 to 2060, while PLTU investments stabilize at 8.0 billion U.S. dollars from 2036 onward. PLTG, PLTMG, and PLTD also show relatively low and stable investment values throughout the projection period.

6. Conclusion

This study examines the evolving dynamics of Indonesia's electricity demand and supply under both the baseline and optimised RUPTL scenarios, aligning with the Net Zero Emission (NZE) 2060 target. In the baseline condition, electricity demand is primarily driven by the household sector, accounting for more than 40% of total consumption. Toward the end of the RUPTL planning horizon, the distribution becomes more balanced across the household, industrial, and commercial sectors. In contrast, the optimised scenario projects a structural transformation of energy use, where the commercial sector becomes the dominant consumer, accounting for nearly 40% of total demand by the final projection year. On the supply side, the PLN RUPTL plan gradually increases renewable energy utilisation through the expansion of hydropower (PLTA) and geothermal (PLTP). However, coal-fired (PLTU) and gas-fired (PLTGU) plants continue to dominate installed capacity. The optimised scenario, however, envisions a full phase-out of fossil-based generation by 2060. Fossil fuel plants, which account for nearly 90% of installed capacity in 2024, are projected to decline to around 65% by 2034 before being completely retired by 2060, consistent with the NZE pathway. Both the baseline and optimised scenarios ensure sufficient generation capacity to meet Indonesia's growing electricity demand, maintaining system reliability throughout the transition period. Environmentally, the optimised pathway achieves complete decarbonisation of the power sector by 2060, eliminating greenhouse gas emissions from electricity generation. Economically, the transition toward a fully decarbonised power system requires substantial investment, with cumulative capital expenditures estimated at approximately USD 653,4 billion by 2060. These findings underscore the crucial need for robust investment frameworks, sustainable financing mechanisms, and policy consistency to mobilise both domestic and international capital. Overall, achieving Indonesia's long-term decarbonisation and energy security objectives will depend on integrated planning, technological innovation, and strong institutional commitment to accelerate the adoption of renewable energy.

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