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Optimization of Electricity Transition Scenarios Toward Net Zero Emissions by 2060 in Indonesia: Resource Analysis and System Reliability.

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Abstract. *Indonesia faces a significant challenge in fulfilling its commitment to the Enhanced Nationally Determined Contribution (ENDC) by 2030 and achieving net-zero greenhouse gas (GHG) emissions by 2060. This necessitates a transformation in the electricity sector, requiring the adoption of low-emission, reliable, and cost-effective technologies. This study develops three electricity transition scenarios toward net-zero emissions using the Long-range Energy Alternatives Planning (LEAP) system: (1) Current Strategy (CS), which emphasizes coal-based generation with Carbon Capture and Storage (CCS); (2) Renewable Energy-Based Transition (ET), which prioritizes solar, wind, hydro, and geothermal energy; and (3) Enhanced Renewable and New Energy Transition (EBT), which integrates renewables with nuclear and hydrogen baseload power. The model results indicate that electricity demand in 2060 is projected to be 1,808 TWh, with a peak load of 245 GW. The required generation capacity for each scenario is 565 GW (CS), 758 GW (ET), and 1,211 GW (EBT). Peak emissions are expected in 2031, at 440 $MtCO_2$ (CS) and 439 $MtCO_2$ (ET and EBT). By 2060, zero emissions are achieved in the ET and EBT scenarios, while the CS scenario still emits 103 $MtCO_2$. All scenarios meet the ENDC 2030 emission-reduction target. System reliability is highest in the EBT and CS scenarios, while emission reductions are most significant in the ET and EBT scenarios. These findings underscore the importance of a rapid expansion of renewable energy, the deployment of new energy technologies, and the utilization of carbon capture technologies in achieving Indonesia's climate and energy security targets. The integration of dispatchable technologies, such as nuclear and hydrogen, alongside robust storage solutions, is crucial for ensuring system reliability amid the increasing share of variable renewable energy.*

Keywords: *LEAP Modeling, Renewable Energy, Emission Reduction, Electricity Generation, ENDC 2030, Net Zero Emission*
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INTRODUCTION

Electricity is one of the fundamental needs of modern society, and with Indonesia's electrification rate approaching 100% [1], it indicates that nearly the entire Indonesian population relies on electrical energy for their daily activities. Per capita electricity consumption is a key indicator of whether a country's development status is developed or developing [2].

From 2020 to 2024, Indonesia's per capita electricity consumption was recorded at 1,411 kWh/capita at the end of 2024, showing a significant increase in electricity consumption per capita in recent years [3]. However, this figure still lags significantly behind those of other ASEAN countries. Singapore (8,200 kWh/capita) and Brunei (7,000 kWh/capita) exhibit much higher electricity consumption per capita, reflecting their higher levels of industrialization and living standards. Malaysia (4,800 kWh/capita), Thailand, and Vietnam (2,000 - 2,500 kWh/capita) also surpass Indonesia, reflecting more advanced economic development and energy infrastructure [4].

The National Long-Term Development Plan (RPJPN 2025-2045) outlines eight priority agendas for Indonesia Emas 2045, including socio-cultural and ecological resilience. Key aspects of this agenda are a quality living environment, energy resilience, water and food independence, and resilience to natural disasters and climate change [5]. These goals align with Indonesia's commitment to reduce emissions as stated in the Paris Agreement. To achieve a "golden Indonesia," several targets have been set, including economic growth and a per capita electricity consumption of up to 5,000 kWh/capita by 2060. As electricity consumption increases, the readiness of the electricity infrastructure must also improve, particularly in terms of national electricity generation capacity [6].

Efforts to reduce electricity sector emissions include accelerating the development of renewable energy for electricity supply, prohibiting the construction of new coal-based PLTUs as an effort to support the transition to low-emission energy, and increasing renewable energy generation. Strict exceptions apply to projects that were included in the RUPTL before the regulation was issued, particularly those designated as national strategic projects. These projects must commit to reducing emissions by 35% within ten years of operation and have a maximum operating period of up to 2050. The early retirement of existing PLTUs for PLN and developers with special provisions is also part of the strategy [7].

The development of power plants must be carefully planned to ensure a sufficient electricity supply and prevent deficits or oversupply in the power system. A power deficit results in outages, while oversupply leads to over-investment, both of which increase the cost of power generation [6]. This study aims to develop three distinct electricity transition scenarios toward net-zero emissions by 2060 using LEAP modeling, with an emphasis on resource availability, system reliability, and cost-effectiveness. The scenarios are designed to inform policymakers in developing coherent pathways for achieving Indonesia's climate and energy security targets.

Materials and Methods

Time and Location

This study uses 2020 as the base year for data processing and analysis in the energy sector, specifically the electricity sub-sector, to support national policies aimed at realizing the Enhanced Nationally Determined Contribution (ENDC) by 2030 and achieving Net Zero Emissions in the electricity sub-sector by 2060. In Indonesia (**Figure 1**), electricity generation is divided into two main sources based on ownership: (1) power plants owned by PLN (State Electricity Company) and (2) power plants owned by private companies or Independent Power Producers (IPPs), either connected to the PLN network or operated as captive power for specific areas.

Material

This research employs a quantitative method with a forecasting approach to estimate the potential use of energy sources for electricity generation until 2060. The equipment used in this research includes a Windows OS-based system equipped with LEAP (Low Emissions Analysis Platform) software and Microsoft Excel 2019 for data processing and preliminary calculations.

The data used in the LEAP model (Figure 2) sourced from the Government of the Republic of Indonesia, including laws, government regulations, presidential regulations, supporting regulations from related ministries, and the electricity sector of PT PLN (Persero). These include the Paris Agreement Ratification Law (Law no. 16 of 2016), the National Energy General Plan (Presidential Regulation No. 22/2017), Indonesia's NDC 2030 (2016), the GHG emission inventory in the energy sector (ESDM 2020), ENDC 2022, Statistics Indonesia (BPS), the National Electricity General Plan (RUKN 2025-2060), the Electricity Supply Business Plan (RUPTL 2025-2034), and reports from the Ministry of Energy and Mineral Resources, PLN Statistics, and other supporting journals.

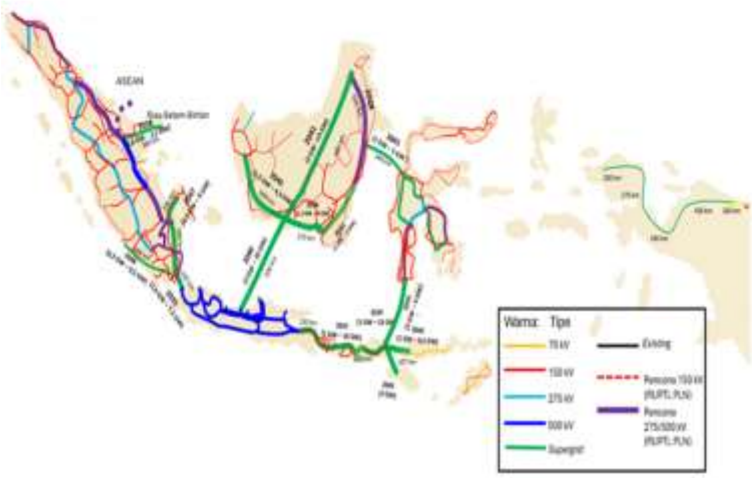

Figure 1. Map of Indonesia Region (RUKN)

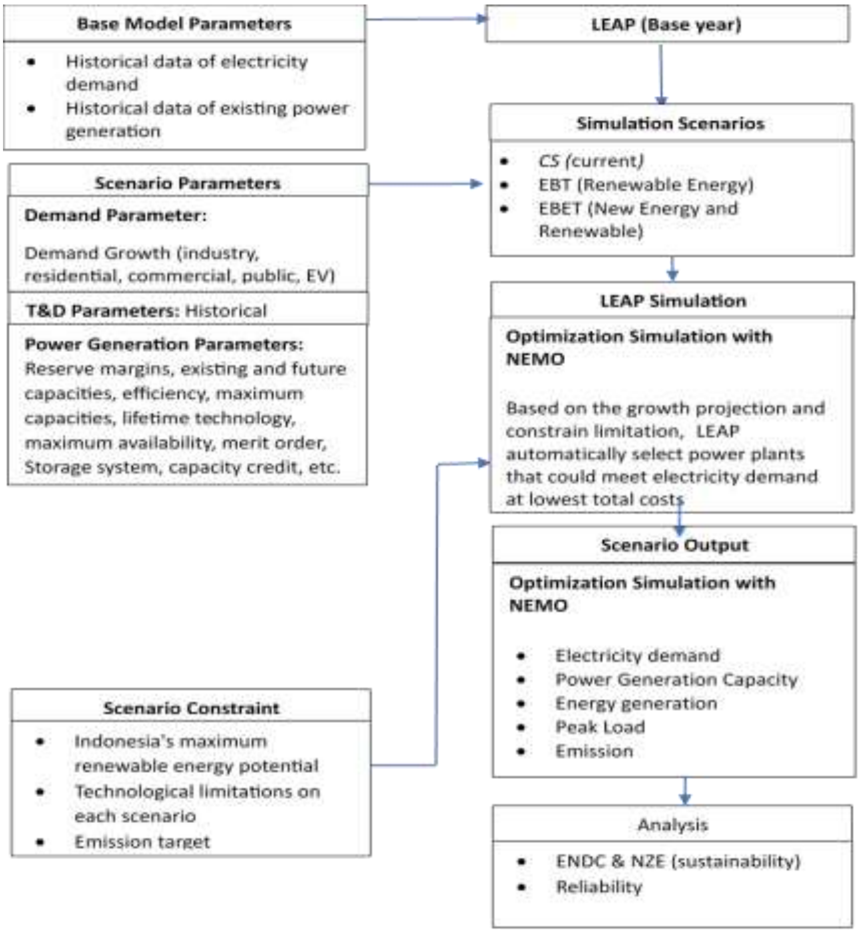

Figure 2. LEAP Framework

Overview of Indonesia's Electricity Sector

The Indonesian economy demonstrated resilience in 2024, with stable GDP growth of 5.03%, reaching IDR 22,139 trillion (approximately USD 1.3 trillion) and a GDP per capita of USD 4,960 [8]. Additionally, the Indonesian electricity sector experienced a rapid increase in energy demand. Indonesia's per capita electricity consumption in 2024 was recorded at 1,411 kWh, with a growth rate of approximately 5.53% from the previous year. The electrification ratio continues to grow, approaching 100% [1].

The Indonesian government aims for an average economic growth rate of 5.4% per year until 2060, with a target increase of 6.1% from 2025 to 2045 and 4.5% from 2046 to 2060 [6]. Indonesia is the fourth-largest population in the world, with approximately 277.5 million people in 2024, projected to reach around 323 million by 2060 [9]. This demographic trend indicates that electricity demand in Indonesia will continue to grow and is expected to increase more than fivefold by 2060 [6].

By the end of 2024, the national electricity generation capacity had reached 100 gigawatts (GW), with a peak load recorded at 61 GW, a significant increase from 58 GW in 2023 [10]. The capacity mix remains dominated by coal-based power plants (53%), followed by gas (26%), and an increasing contribution from renewable energy (15%), including hydro, geothermal, biomass, and solar [1]. Over the past year, coal-fired power plant (PLTU) capacity increased by 15%, from 46 GW in 2023 to 53 GW in 2024, with an additional 7 GW from IPPs and captive sources [11][12].

Table 1. Primary energy potential [13]

Energy	Reserves in Indonesia
Coal (primary)	31.7 1 billion tons
Natural Gas (primary)	35.3 0 TSCF
Petroleum (primary)	4.7 billion barrels
Uranium (new)	90,000 tons
Thorium (new)	140,000 tons
Hydro	± 95 GW
Hydro Pump Storage	800 TWh
Geothermal	± 24 GW
Biomass	± 53.4 GW
Solar	± 3,294.4 GWp
Wind	± 155 GW
Tidal	± 63 GW

Methodology and Data

Model Review

A suitable modelling tool is essential for long-term planning to support optimal investment allocation. The LEAP model was selected for this study due to several key advantages. First, LEAP can accommodate various characteristics crucial for analyzing the energy sector, particularly in developing countries. Second, it is freely available to students, non-profit organizations, and academic institutions in these regions. Additionally, LEAP is recognized for its user-friendly interface and provides comprehensive online support that is readily accessible to all users.

Lastly, the LEAP model has been adopted by thousands of organizations across more than 190 countries, including government agencies, academic institutions, non-governmental organizations, consulting firms, and energy utilities. It has been applied at multiple scales, ranging from local and provincial levels to national, regional, and global analyses.

LEAP has been widely utilized in numerous studies to assess CO_2 mitigation in the power sector worldwide. The model has supported the exploration of alternative energy development scenarios in Indonesia [18, 19, 20, 21], Malaysia [23], Pakistan [24], Japan [25], and several ASEAN member countries [26]. As an open-access platform, LEAP provides essential features for evaluating the technical, economic, and environmental dimensions of electricity system expansion.

Validation of the Indonesian LEAP Model

Model Settings

Model validation is necessary to ensure the reliability of the LEAP model by comparing its results with actual Indonesian data for 2020–2024. The LEAP analysis is populated with Indonesian electricity system data covering the base years 2020–2024. The model's architecture, as illustrated in Figure 3, consists of three principal modules: demand, transformation, and resources, with power generation represented in the transformation module. The generation submodule models how supply meets specified demand using a set of input parameters (see Table 1). Typical outputs from the model include added capacity, technology mix, electricity production, greenhouse gas emissions, and cost estimates.

The LEAP model runs are initialized with 2020 as the starting year, projecting the expansion of Indonesia's generation fleet through 2024. According to HEESI, the main technologies employed during this period are coal-fired steam turbines (PLTU), natural gas combined-cycle plants (PLTGU), open-cycle gas turbines (PLTG), gas engines (PLTMG), diesel gensets (PLTD), hydropower (PLTA), geothermal (PLTP), wind (PLTB), and solar PV (PLTS).

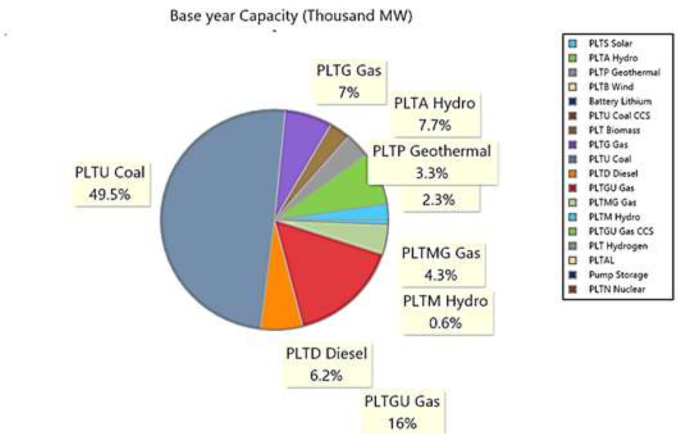

Figure 3. Power Generation Mix in Indonesia in 2020 [1].

Table 2. Input – output parameters and comparison of actual data with LEAP simulation

Input Output parameters			Data comparison		
Input Parameter	Output Model	*Data for Validation*	*Current*	*Estimate*	*Deviation*
Electricity Demand (2020), Transmission & Distribution Losses (2020), Load Shape, Power Generation Capacity, Efficiency, Investment Cost, Operation Cost, Fuel Emission	*Electricity generation (2024), Capacity Added (2024), CO2 Emission*	*Historical Electricity Generation (2024), Historical Capacity Addition (2024), CO2 Emission*	101 GW, 462369 TWh (MEMR.2025), 356 $MTCO_2e$ (Energy Self-Sufficiency & Powering Nation (2024))	97.2 GW, 461600 TWh, 351 $MTCO_2e$	-3.76%, 0.16%, -1.42%

Scenario Development to 2060

Three capacity expansion scenarios were developed for Indonesia's electricity system. These scenarios are based on modifications to LEAP assumptions regarding power generation technology choices and/or energy source types, all aimed at reducing CO_2 emissions in line with Indonesia's commitments under the Paris Agreement and the ENDC.

Capacity additions are aligned with the Electricity Supply Business Plan (RUPTL) for PLN’s business areas (medium-term) and the plan to increase renewable energy generation capacity outlined in the RUKN, up to the maximum potential limit. Additional generators for captive power are included to support the national mineral industry, in accordance with the RUKN (2025–2060).

The CS scenario increases generating capacity based on current conditions, guided by the National Development Planning Agency (RUKN) for capacity size and technology. In the EBT scenario, generating capacity is increased using 100% renewable energy, in line with available reserves. The EBET scenario increases capacity with both new and renewable energy sources to meet electricity demand.

Data Input

The data sources and methodology for calculating the parameters of the Indonesian electricity system are presented in Table 3. Although LEAP's default values can be used, most of the data is sourced from a national level. Therefore, the majority of input parameters are collected from government and national electricity company reports.

Table 3. Summary of model input parameters

Input parameters	Mark	Data source
Per capita electricity growth target	(1.8 MWh/capita – 5 MWh/capita)	RUKN [6]
Residential growth	113 – 502 TWh	RUKN [6] , HEESI [1]
Industry Growth	146 – 774 TWh	RUKN [6] , HEESI [1]
Commercial Growth	43 – 245 TWh	RUKN [6] , HEESI [1]
Public Growth	16 – 94 TWh	RUKN [6] , HEESI [1]
Electric Vehicles	0.001 – 198 TWh	RUKN [6]
Transmission and distribution of losses	9.12 - 7%	PLN Statistics [29]
System Load Shape	Attachment	RUPTL [28]
Reverse Margin	30%	RUPTL [28]
Environmental parameters	National fuel parameters	ESDM [30]
Discount Rate	9%	ADB [31]

A limitation of LEAP is its inability to model the expansion of transmission and distribution networks. Consequently, this analysis assumes an unconstrained grid, where electricity can be delivered at any time to any load point. Therefore, transmission-line costs are excluded from the cost estimates. In LEAP, electricity output is driven by the demand projections entered in the demand module. The generation submodule then selects the technologies required to satisfy that demand.

Candidate technologies considered for capacity additions in this study include coal-fired plants (PLTU), open-cycle and combined-cycle gas plants (PLTG, PLTGU), diesel generators (PLTD), gas engine units (PLTMG), hydropower (PLTA, both small- and large-scale), geothermal (PLTP), biomass (PLTB), wind (PLTB), solar PV (PLTS), nuclear (PLTN), coal and gas plants with carbon capture and storage (CCS-PLTU, CCS-PLTGU), ocean-current plants (PLTAL), Battery Energy Storage Systems (BESS), and Pumped Storage (PS).

Data on existing Indonesian power plants were sourced from HEESI and RUKN and include installed capacities by technology. Parameters such as thermal efficiency, electricity output, capacity factors, capital expenditures, and operating costs were taken from the **Generation and Storage of Electricity 2024** catalog [32]. Accurate representation of current plant characteristics is essential for establishing a reliable base year and framing future expansion scenarios. The current fleet capacities are listed in the appendix and are used as the starting point for projected capacity additions. Throughout the model runs, these technical and economic parameters are held constant. Fuel cost assumptions—coal [33] and natural gas [34]—are drawn from the Ministry of Energy and Mineral Resources, nuclear fuel costs from NZWI [35], and biomass fuel costs from the CREA study [36].

Table 4. Technology characteristics [32]

Technology	Lifetime (years)	Efficiency (%)	Availability (%)	Capacity Credit (%)	Capital Cost (2020 MUS$/MW)	Fixed OM Cost (2020 US$/MW)	Variable OM Cost (US$/kW)	Fuel Cost (US$)
		2020 - 2060			2020 - 2050	2020 2050	2020 2050	
hydroelectric power plant	50	90 - 95	41	51	2.2 - 1.96	43000 - 38000	0.74 - 0.66	
Micro Hydro Power Plant	50	80	41	58	2.7 - 2.4	60400 - 54000	0.57 - 0.51	
Steam Power Plant (SC)	30	37 - 39	80	100	1.6 - 1.5	47000 - 44100	1.4 - 1.3	70/ton
Gas Power Plant	25	33 - 39	80	100	1.12 - 0.99	26500 - 24900	3.6 - 3.4	8/MMbTu
Combined Cycle Power Plant	25	50	80	100	1.08 - 0.95	26800 - 25200	2.6 - 2.4	
Geothermal Power Plant	30	15 - 17	80	100	4.4 - 3.96	110000 - 99000	0.39 - 0.35	
Diesel Power Plant	25	45 - 47	80	100	0.91 - 0.89	9120 - 8847	7.3 - 6.61	96/barrel
PLTMG	25	45 - 47	80	100	0.91 - 0.89	9120 - 8847	7.3 - 6.61	
wind power plant	30	100	25	35	1.65 - 0.95	40000 - 30000	0	
Solar Power Plant	30	100	17	22	0.96 - 0.48	7500 - 6100	0.4 - 0	
Biomass Power Plant	30	31	80	100	2.28 - 1.82	54000 - 43200	3.4 - 2.72	51/ton
CCS Steam Power Plant	30	29 - 31	80	100	3.84 - 2.77	97000 - 72200	4.5 - 3.7	
CCS Combined Cycle Power Plant	30	48 - 52	80	100	2.39 - 1.72	59000 - 37800	4.96 - 3.62	
Micro Hydro Power Plant	40	90	40	40	5.8 - 5.4	75048 - 37843	12 - 8	
Nuclear Power Plant	60	34 - 40	80	100	5.8 - 4.5	127000 - 113000	2.4 - 2.2	6/MWh
Hydrogen Powerplant	25	30	80	100	1,134 - 0.9975	28140 - 26460	2.73 - 2.52	38 ~ 13 /GJ
PS	60	80	80	25	1.2 - 1.2	10000 - 10000	0.94	
BESS	15	80 - 90	80	90	0.47 - 0.23	15000 - 7350	2 - 1.6	

Results and Discussion

Electricity Demand and Peak Load

Model results indicate that national electricity demand in 2060 will reach 1,808 TWh (Figure 4), representing an average annual growth of approximately 4.2% from 2022 to 2060. The peak instantaneous load is projected at 245 GW (Figure 4). The sectoral distribution reveals that the industrial sector accounts for the largest share of consumption (42.6%), followed by the residential sector (27.6%), the commercial sector (13.5%), electric vehicles (10.9%), and the public sector (5.2%).

Power *Generation* Capacity

Power generation capacity increases across all scenarios (Figure 5). The highest increase occurs in the Renewable (EBT) scenario, reaching 1,211 GW, with solar PV accounting for 50% of the installed capacity. The lowest capacity is observed in the Current (CS) scenario, at 565 GW, dominated by coal power plants with CCS and solar PV.

The use of BESS (Battery Energy Storage Systems) is also highest in the Renewable (EBT) scenario and lowest in the Current (CS) scenario. The New Renewable (ET) scenario falls between the two, both in terms of total installed capacity and BESS capacity.

The CS scenario models capacity expansion using a more diverse set of generation technologies, including fossil-fuel power plants equipped with Carbon Capture and Storage (CCS) mitigation systems. Several technologies within this scenario are still in the development stage, such as hydrogen, nuclear, and CCS. Hydrogen utilization has undergone a 100% combustion trial in micro gas turbines [40]. Meanwhile, CCS development remains suboptimal, facing various limitations, including financial constraints, regulatory uncertainty, technological risks, and challenges in attracting private investment [41]. Additionally, the carbon capture performance of CCS facilities remains below target levels [42][43].

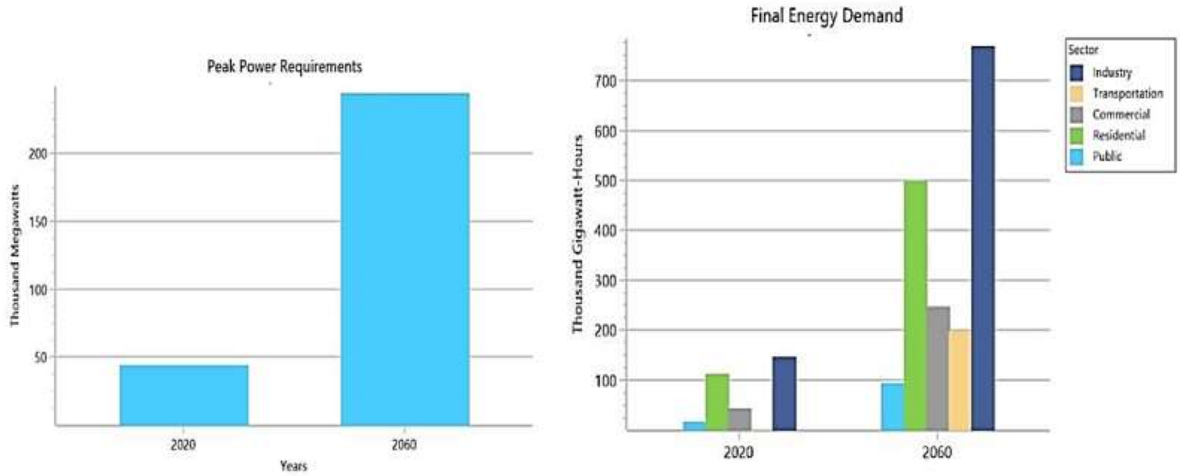

Figure 4. Electricity Demand and Peak Load

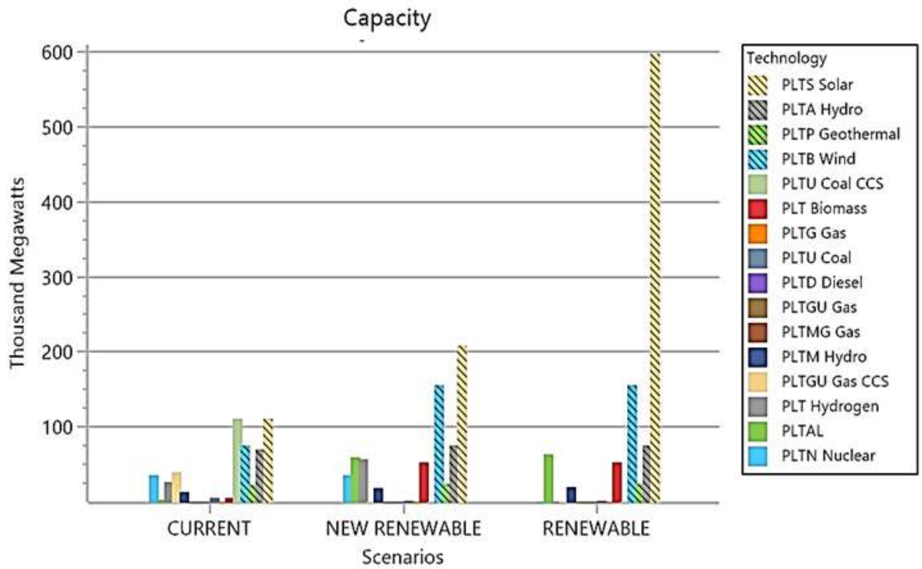

Figure 5. Power Generation Capacity

The addition of nuclear technology in the New Renewable (EBT) scenario provides a significant impact on reducing emissions. It can operate as a baseload, substituting for coal- and gas-fired power plants (PLTU and PLTGU). Nuclear technology has relatively high efficiency (34%) and a reliable capacity credit [45]. However, nuclear utilization still lacks full public acceptance. Implementing this scenario requires broad stakeholder support, along with extensive public outreach and enhanced safety and security measures that meet the highest standards [44][46].

Electricity Generation

Electricity generation in each scenario corresponds to the types of technologies installed. In the **CS** scenario, generation is dominated by coal-fired power plants with CCS (PLTU + CCS). In the **Renewable (EBT)** scenario, several technologies contribute in relatively balanced proportions, including biomass (PLTBio), wind (PLTB), and solar PV (PLTS). Meanwhile, the **ET** scenario is dominated by solar PV, which accounts for more than 40% of total electricity generation.

As shown in **Figure 6**, the energy generation mix across all scenarios varies significantly, with different shares of renewable and fossil-fuel-based technologies contributing to total generation.

Coal-fired power plants equipped with CCS have high availability, and their electricity generation is equivalent to five times the output of solar PV (PLTS) at the same installed capacity. As a result, total electricity generation exceeds the consumption requirement by around 7%, due to losses in transmission and distribution networks.

Achievement of ENDC 2030 and NZE 2060

It is estimated that by 2030, the energy sector will still produce approximately 440 million tons of CO_2e, primarily from the combustion of fossil fuels. Emissions are dominated by coal-fired power plants (PLTU) and natural gas–based power plants, including PLTG, PLTGU, and PLTMG.

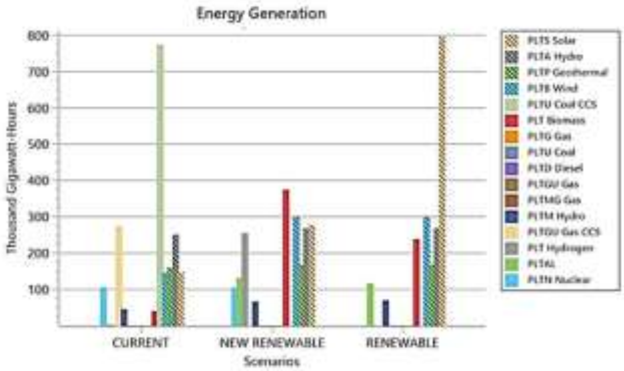

Figure 6. Energy Generation for All Scenarios

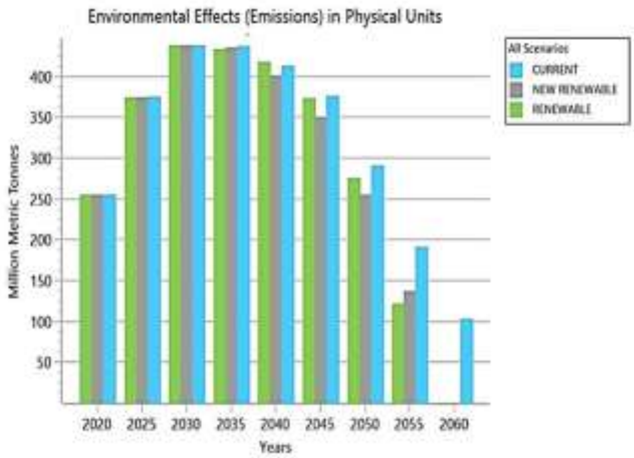

Figure 7. Emissions for All Scenarios

As shown in **Figure 7**, emissions across all scenarios are influenced by the mix of power generation technologies. The updated emission reduction target in ENDC 2024 requires the energy sector to reduce emissions by 12.5% by 2030, an increase from the previous target of 11%. The power generation sub-sector is the most significant contributor to energy sector emissions, accounting for 37.5% [27]. Using this proportion as the basis for allocating emission reduction responsibilities, the required reduction from the power generation sub-sector in 2030 is estimated to be 165 million tons of CO_2e, relative to a baseline of 625 million tons of CO_2e. All three scenarios achieve the ENDC 2030 emission reduction target. However, for the net-zero emission (NZE) 2060 target, the **CS** scenario does not meet the required emission trajectory.

Power System Reliability

The increase in power generation capacity is consistent with the growing demand for electricity in society. The highest capacity expansion occurs in the ET scenario, followed by the EBT and CS scenarios.

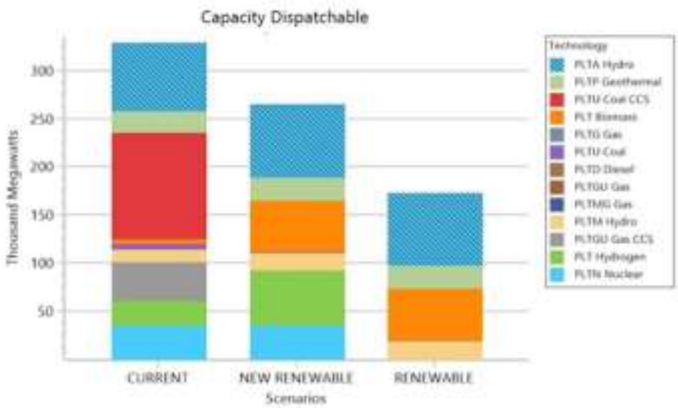

Figure 8. Dispatchable Capacity Power Generation

As shown in Figure 8, the large capacity in the ET scenario is driven by the dominance of variable/intermittent generation technologies, which have low availability and are not continuously dispatchable (low capacity credit). One of the most critical aspects of the power system is system stability. In the EBT scenario, the utilization of 100% renewable energy—most of which is derived from VRE—can increase the vulnerability of the power system [47]. The highest level of power system security is achieved in the CS and EBT scenarios, where the installed capacity of dispatchable power plants exceeds the projected peak load.

Conclusions

The electricity demand in 2060 is projected to reach 1,808 TWh, with energy generation of 1,944 TWh and a peak load of approximately 244 GW. The total generation capacity required will vary across scenarios. The reduction of power-sector emissions to achieve the ENDC target in 2030 and net-zero emissions by 2060 can be pursued through the massive expansion of renewable energy, the deployment of new energy technologies, and the utilization of carbon capture technologies. Several low-emission technologies are still in the development stage, such as ocean current power (PLTAL), BESS, hydrogen, and CCS (carbon capture and storage). New energy sources such as nuclear and hydrogen can replace coal as baseload generators due to their dispatchable characteristics, which help maintain system reliability. The limitations of variable renewable energy (VRE) lie in its intermittency, low capacity credit, and availability only at certain times (e.g., solar PV). Achieving emission targets and ensuring system reliability are inseparable components of future energy planning.

Recommendation

Long-term energy planning models require periodic evaluation to ensure that the selected technological development pathways remain appropriate, particularly for technologies that are still in the development or experimental stage. This is essential to maintain the effectiveness of planning efforts in meeting emission-reduction targets and ensuring system reliability.

Author Contributions

N: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **RB**: Supervision, Methodology, Validation, writing – Review & Editing; **MSR**: Supervision, Validation, Writing – Review & Editing.

Conflicts of interest

There are no conflicts of interest to declare.

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