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**RESEARCH PAPER**

# Renewable energy pathways in Indonesia's long-term strategy for low carbon and climate resilience 2050

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**Abstract.** This paper explores renewable energy pathways in Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050, assessing their potential to reduce greenhouse gas (GHG) emissions and support long-term economic sustainability. A comparative scenario analysis, Business-as-Usual (BAU) versus a low-carbon scenario, was conducted using projections of capacity growth, emissions reduction, and techno-economic performance. Net Present Value (NPV) and Levelized Cost of Energy (LCOE) were calculated for solar PV, wind, geothermal, hydropower, and biomass. Results show that biomass and geothermal provide the lowest LCOEs due to high-capacity factors, while solar PV and wind benefit from declining technology costs. Under the low-carbon scenario, GHG emissions are reduced by nearly 50% by 2050 compared to BAU, averaging about 10 million tones $CO_2$-equivalent per year. Sensitivity analysis identifies investment cost and capacity factor as the most critical variables. The findings highlight that targeted policy incentives, infrastructure investment, and region-specific planning are essential to accelerate Indonesia's clean energy transition and achieve national climate goals.

**Keywords:** Renewable energy; Greenhouse gas; Feasibility analysis; Low-carbon development.

## 1. Introduction

Renewable energy plays a vital role in addressing the global climate crisis, offering a sustainable pathway to significantly reduce greenhouse gas (GHG) emissions and decarbonize national energy systems. Indonesia, with a population exceeding 281 million (BPS, 2025), the fourth largest in the world, is a major contributor to global emissions and also one of the most climate-vulnerable nations due to its geographic and economic conditions. In response, the Government of Indonesia has adopted the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050 (Government of Indonesia, 2021) which outlines ambitious yet necessary targets to reach net-zero emissions and enhance climate resilience by mid-century. A central pillar of this strategy is the transformation of the energy sector through increased deployment of renewable energy, reduced fossil fuel dependency, and the integration of sustainable technologies (Siregar, 2024).

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The global pursuit of mitigation of climate change has led numerous countries to explore and implement renewable energy pathways. Studies focusing on these transitions (Fernandez et al., 2024; Rotich et al., 2024; Singh et al., 2023; Xu et al., 2024) provide valuable insights into the technical, economic, and policy dimensions of integrating renewable energy sources into national grids.

A comprehensive review by Gulagi et al. (2021) examined the feasibility of achieving 100% renewable energy systems across multiple countries. The study concluded that such transitions are technically and economically viable, emphasizing the importance of policy support and technological advancements in facilitating these shifts. In the case of the Philippines, studies have shown that transitioning to a 100% renewable energy system is not only technically feasible but also more economically cost-competitive than the existing fossil fuel-based system.

Todd and McCauley (2021) examined South Africa's energy transition and revealed that socio-political and technological dynamics significantly hinder progress, especially due to the dominant influence of the fossil fuel industry and Electricity Supply Commission (ESCOM). This resistance has marginalized township and rural communities, who continue to face energy injustice and limited access to reliable energy services. The study critiques traditional approaches to energy justice for their overemphasis on process over outcomes and advocates for a shift toward measuring justice through tangible results, such as decarbonization, energy security, and affordability. The authors argue that linking energy justice more closely to global decarbonization goals would enhance its impact. Additionally, the pace of transition is constrained by societal barriers and weak policy frameworks. The study urges the South African government to restructure ESCOM, attract foreign investment, and build a coalition for change, including empowering municipalities. These steps are essential for achieving an equitable, accelerated transition to renewable energy.

The European Union has been at the forefront of setting ambitious climate and renewable energy targets. Under the Europe 2020 Strategy, the EU aimed for a 20% share of renewable energy in gross final energy consumption by 2020, alongside a 20% reduction in greenhouse gas emissions and a 20% improvement in energy efficiency (EUR-Lex, 2020). These targets have been instrumental in driving renewable energy adoption across member states.

Sulaimanova et al., (2023) conducted a bibliometric analysis of clean energy research in Central Asia from 1991 to 2022, revealing a shift in focus from fossil fuels to renewable energy. While the volume of publications on renewable energy has grown in recent years, research specifically on solar, wind, and bioenergy remains limited. The study identified China, Japan, Kazakhstan, and Russia as the most active contributors in the latest period, whereas the USA, UK, Netherlands, Germany, and Turkey led during 2012–2016. Strong institutional collaborations were found among Nazarbayev University, the Asian Development Bank Institute, the CAREC Institute, and Al-Farabi Kazakh National University. This analysis sheds light on the evolving academic networks and collaboration trends in energy transition research within the region. The authors emphasize the usefulness of such bibliometric insights for potential collaborators and funders and recommend broader database exploration, especially incorporating Russian-language literature, to gain a more comprehensive understanding of clean energy trends.

Elshazly (2021) highlighted the crucial role of Egypt's energy sector in achieving energy security, economic development, and environmental sustainability. As the most populous country in North Africa and the Arab region, Egypt has faced rising energy demand, which intensified during the 2014 fuel shortages. These challenges prompted the government to accelerate its renewable energy transition to diversify the energy mix and meet growing needs. The study outlines Egypt's strategic framework for developing renewable resources and identifies key challenges to achieving a low-carbon economy, emphasizing the importance of policy action in supporting sustainable energy development.

Despite these global insights, Indonesia faces distinct challenges. Unlike many peer countries, Indonesia still has limited techno-economic scenario analyses tailored to its LTS-LCCR 2050. Financing renewable projects remains difficult due to high perceived risks, inconsistent regulations, and underdeveloped support mechanisms. These gaps underscore the need for integrated scenario-based studies that evaluate both economic feasibility (e.g., Net Present Value (NPV) and Levelized Cost of Energy (LCOE)) and emissions reduction potential within the Indonesian context.

Given the complexity and magnitude of Indonesia's energy transition, it is crucial to formulate well-defined, evidence-based renewable energy pathways that are technically feasible, economically viable, and socially inclusive. This paper aims to identify and analyze potential renewable energy pathways that align with the LTS-LCCR 2050 vision. Specific objectives include: (1) modeling renewable energy deployment scenarios across key technologies such as solar PV, hydropower, biomass, geothermal, wind, and ocean energy; (2) assessing the effectiveness of various policy incentives, such as feed-in tariffs, renewable portfolio standards, and fiscal support, in accelerating renewable energy adoption; and (3) conducting sensitivity analyses to understand how changes in investment cost, policy implementation, and technology learning rates influence the achievement of the LTS-LCCR targets.

The study applies a bottom-up, scenario-based modeling approach using a custom spreadsheet-based model developed specifically for this research. The model was constructed in Microsoft Excel, incorporating official datasets, emission factors, and cost parameters derived from national and international sources. To ensure consistency and reliability, the equations for NPV, LCOE, and sensitivity analysis were formulated based on established methods in the literature (IRENA, 2023; Le, 2021). Artificial Intelligence tools, such as ChatGPT, were utilized to support the structuring of analytical formulas and scenario design, but all calculations, data inputs, and interpretations were validated manually by the author. This approach enables transparency and replicability while allowing for flexibility in tailoring the scenarios to Indonesia's specific policy and resource context.

## 2. Methods

This study employs a mixed-method approach that integrates qualitative policy analysis and quantitative scenario modeling to explore renewable energy pathways in Indonesia's LTS-LCCR 2050. The methodological framework consists of four key components: data collection, scenario development, and analytical modeling. This comprehensive approach ensures a holistic assessment of how renewable energy technologies can support Indonesia's transition to a low-carbon and climate-resilient future.

Data for the study were gathered from various sources to ensure robustness and reliability. Policy and regulatory documents, including the National Energy Policy (KEN), the National Energy General Plan (RUEN)(Dewan Energi Nasional, 2017), MEMR regulations (particularly MEMR No. 2/2024), and Indonesia's Nationally Determined Contributions (NDCs) (ClimateScorecard.org, 2024; Handayani et al., 2022), provide the foundation for understanding the current policy landscape. Statistical data on renewable energy capacity and generation were obtained from the Ministry of Energy and Mineral Resources (MEMR), Perusahaan Listrik Negara (PLN) reports, and international databases such as the International Renewable Energy Agency (IRENA) (2021) and the International Energy Agency (IEA) (2024). Additionally, peer-reviewed journals, industry reports, and conference proceedings were reviewed to incorporate the latest insights into renewable energy technologies and market trends.

To evaluate Indonesia's renewable energy pathways, two primary scenarios were developed. The Business-as-Usual (BAU) scenario assumes the continuation of existing energy policies and trends without significant shifts in policy or technology. This scenario projects renewable energy development based on current growth rates and planned projects. In contrast, the low-carbon scenario aligns with the objectives of the LTS-LCCR 2050, envisioning aggressive deployment of renewable energy technologies, enhanced energy efficiency measures, and comprehensive policy reforms. This scenario incorporates accelerated investments in solar, geothermal, hydro, biomass, and wind energy, alongside the integration of smart grid technologies and energy storage systems. It also emphasizes the electrification of the industrial and transport sectors using renewable energy sources.

A combination of analytical tools and models was employed to simulate energy pathways and assess their impacts. GHG emissions were estimated using emission factors from the Intergovernmental Panel on Climate Change (IPCC) (2006) guidelines and Indonesia's national inventories (Climatescorecard.org, 2023). The GHG emissions ($E$) were calculated using Equation (1).

$$E = \sum_{i=1}^{n}(A_i \times EF_i) \tag{1}$$

Where, $E$ is the total GHG emissions (in tons of $CO_2$-equivalent), $A_i$ is the activity data for the energy source $i$ (e.g., energy produced or consumed), $EF_i$ is the emission factor for the energy source $i$ (in tons of $CO_2$-equivalent per unit of activity), $n$ is the number of energy sources considered.

A cost-benefit analysis was conducted to evaluate the economic feasibility of renewable energy deployment by comparing costs, benefits, and policy incentives. The NPV of renewable energy projects was calculated using Equation (2) (Le, 2021):

$$NPV = -I + \sum_{t=1}^{T}\frac{O_t}{(1+r)^t} \tag{2}$$

Where, $I$ is the initial investment cost (USD), $O_t$ is the annual operation and maintenance costs (USD), $r$ is the discount rate (assumed 8%), $T$ is the project lifetime (25 years).

LCOE measures the average cost per kWh of electricity generated over the plant's lifetime. It is calculated using Equation (3).

$$LCOE = \frac{NPV}{\sum_{t=1}^{T}\frac{E_t}{(1+r)^t}} \tag{3}$$

Where, $E_t$ is annual energy output (MWh), $NPV$ is total present value of investment and O&M costs.

For the sensitivity analysis, the NPV for each technology was adjusted based on three factors. The first factor is policy support ($PS$), which reflects the effect of regulatory incentives and subsidies. Increased policy support was modeled with a 10% increase, while reduced support was modeled with a 10% decrease. The second factor is technology costs ($TC$), representing variations in capital expenditure. To account for potential technological advancements, a 20% decrease in technology costs was modeled. The third factor is a demand growth ($DG$), which considers the impact of increased energy consumption, a 10% increase in energy demand was assumed. The calculation for sensitivity analysis is presented in Equation (4).

$$NPV_{adjusted} = NPV_{base} \times \frac{PS}{TC} \times DG \tag{4}$$

Where, $NPV_{adjusted}$ is the adjusted Net Present Value, $NPV_{base}$ is the base Net Present Value, $PS$ is the policy support factor (1.1 for increased support, 0.9 for decreased support), $TC$ is the technology cost factor (0.8 for reduced costs, 1.2 for increased costs), $DG$ is the demand growth factor (1.1 for increased demand, 0.9 for decreased demand).

Comparative analysis between the BAU and low-carbon scenarios was conducted to evaluate the effectiveness and feasibility of proposed renewable energy pathways in supporting Indonesia's long-term climate and energy goals.

## 3. Result and discussion

### 3.1 Indonesia's long-term strategy for LTS-LCCR 2050 – energy sector

The energy sector is the second-largest source of emissions in Indonesia after AFOLU, with electricity generation and transport as the main contributors. In the government's LTS-LCCR 2050 report, decarbonization is envisioned through higher renewable shares, carbon capture, utilization, and storage (CCUS) integration, and electrification. Rather than restating those official projections, this study builds upon them by modeling alternative pathways (BAU vs low-carbon) to evaluate the techno-economic feasibility and emissions implications. The following sections present the modeled results of renewable energy capacity expansion, emissions trajectories, and cost performance under both scenarios.

Indonesia's electricity demand is currently dominated by the residential, industrial, and commercial sectors, with transportation making up a minor share, mainly limited to trains. However, this is expected to change with the growing adoption of electric vehicles (EVs). Between 2009 and 2019, electricity consumption rose steadily from 135 TWh to 240 TWh, representing an average annual growth rate of 5.9% (ESDM, 2023). As of 2023, household electrification has reached 99.7% in Indonesia, with connections comprising both centralized (on-grid) systems powered by major power plants and decentralized (off-grid) solutions primarily utilizing renewable energy. Looking ahead, the nation aims to achieve full electricity access using a combination of grid extensions, off-grid technologies, and rooftop solar PV installations.

Projections suggest that electricity demand will continue to grow at about 5% annually (Government of Indonesia, 2021). To meet this rising demand, Indonesia will need to invest in new generation facilities, modernize existing infrastructure, and expand transmission networks. Currently, coal is the dominant source of power, supplemented by natural gas, hydropower, and geothermal energy. By 2050, however, the energy landscape is expected to be significantly decarbonized through three main strategies. First, large-scale integration of renewables such as hydro, geothermal, solar, wind, and biomass. Second, broad application of carbon capture and storage/utilization (CCS/CCUS) in coal-fired plants. Third, biomass-coal co-firing with integrated CCS (BECCS). Under the Low Carbon and Climate Resilience Pathway (LCCP), the electricity generation mix in 2050 is projected to consist of 43% renewables, 38% coal, 10% natural gas, and 8% BECCS. The renewable share includes a diverse array of sources such as hydro, geothermal, solar PV, wind, biomass, and biofuels.

To achieve net-zero emissions from coal power generation, around 76% of coal plants will incorporate CCS technology. Projected renewable energy capacities are projected to be substantial, with solar PV leading at 113 GW, hydro at 68 GW, geothermal at 23 GW, wind at 17 GW, biomass at 13 GW, biofuels at 14 GW, and BECCS at 23 GW, capable of delivering negative emissions. Nonetheless, the variable nature of solar and wind energy necessitates their integration with stable baseload power sources like coal to maintain grid reliability.

The carbon intensity of Indonesia's electricity sector is expected to decline sharply to 104 grams of $CO_2$ per kWh, reflecting major strides in decarbonization. Additional focus will be directed toward expanding off-grid and micro-grid solutions, especially in remote regions. These systems rely entirely on renewable energy and incorporate smart micro-grids to ensure efficiency and reliability. Furthermore, the broad adoption of intermittent renewable energy requires sophisticated smart grid technologies to manage supply variability and stabilize the national grid. Such an integrated energy transition strategy will be essential for realizing Indonesia's long-term low-carbon and climate-resilient future.

### 3.2 Renewable energy deployment trends in Indonesia

The renewable energy sector in Indonesia shows significant potential for growth. This potential is driven by national energy policies and climate commitments under the LTS-LCCR 2050 (Government of Indonesia, 2021).

The National Energy Council of the Republic of Indonesia highlights that the country's renewable energy potential is about 441.7 GW overall. Details are shown in Table 1. The main renewable resources include 94.3 GW of hydropower, 28.5 GW of geothermal energy, 32.6 GW of biopower, 207.8 GWp of solar energy, 60.6 GW of wind energy, and 17.9 GW of ocean energy (Dewan Energi Nasional, 2017). Gigawatts-peak (GWp) is the unit used to describe the maximum power output of solar PV systems achievable under standard test conditions (STC). The STC for photovoltaic modules are defined by an irradiance of 1000 W/m$^2$ (1 kW/m$^2$) during full solar noon sunshine, with the panel maintained at a standard ambient temperature of 25 °C and a sea level air mass (AM) of 1.5.

Despite its potential, the contribution of renewable resources to Indonesia's energy supply remains very limited. Figure 1 (Kanugrahan et al., 2022) shows the power generation output, totaling 274.8 terawatt-hours (TWh). As shown, coal dominated the energy mix with a 62.85% share, followed by natural gas at 21.4%, oil at 0.88%, hydropower at 6%, and geothermal energy at 5.11%. Solar photovoltaic (PV) contributed negligibly, while biomass provided 2.98%, and wind energy, together with other renewables, accounted for only 0.17% of the total output.

### 3.3 Renewable energy scenarios toward 2050

The following analysis compares the projected renewable energy capacity growth under the BAU scenario and the low-carbon scenario from 2025 to 2050.

#### 3.3.1 Business-as-usual scenario

In the BAU scenario, renewable energy development is assumed to continue at current growth rates. Under this assumption, no significant policy or technological advancements have been considered. Based on current trends, the total installed renewable energy capacity is not expected to grow significantly, primarily due to dependence on existing infrastructure and limited investment.

The key projections highlight important insights to support informed decision-making and guide future strategies. PV is projected to experience incremental growth, reaching approximately 15 GW by 2050, primarily driven by utility-scale and rooftop solar installations. Geothermal energy is expected to expand steadily to about 9 GW by 2050, although its development remains constrained by high exploration and development costs. Hydropower is expected to experience moderate growth, reaching 25 GW by 2050, with a focus on small and medium hydropower plants. Biomass and waste-to-energy are projected to grow to 7 GW by 2050, supported by waste management initiatives. Meanwhile, wind energy development is expected to remain limited, with capacity reaching only 3 GW by 2050 due to infrastructure and land use challenges. Overall, the BAU scenario results in a total renewable energy capacity of approximately 59 GW by 2050, which is far short of Indonesia’s renewable energy targets and insufficient to meet LTS-LCCR goals.

**Table 1.** Renewable energy potential in indonesia (Peraturan Presiden No 22 Tahun 2017)

| Energy source | Potential |
|---|---|
| Hydro | 94.3 GW |
| Geothermal | 28.5 GW |
| Bioenergy | 32.6 GW |
| Solar | 207.8 GWp |
| Wind | 60.6 GW |
| Ocean | 17.9 GW |

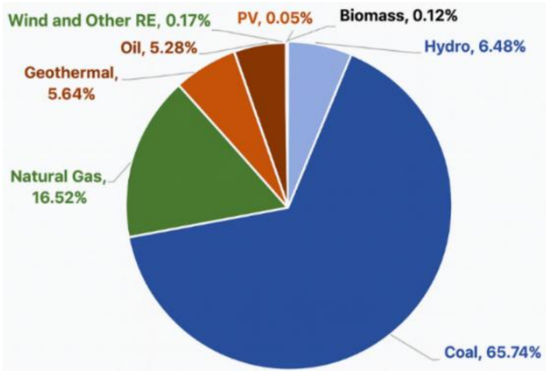


**Figure 1.** Power generation source of Indonesia (Kanugrahan et al., 2022)

**Low-carbon scenario**

The low-carbon scenario assumes aggressive policy interventions and technological advancements that align with Indonesia's 2050 climate goals. This scenario projects an accelerated annual increase of about 3 GW in renewable energy capacity, reaching approximately 110 GW by 2050. The key drivers in this scenario are large-scale solar PV deployment, expanded geothermal utilization, and integration of smart grids and energy storage technologies.

Indonesia's renewable energy potential is diverse, spanning various technologies. Eastern Indonesia (e.g., East Nusa Tenggara, Papua) has the highest solar potential due to high solar irradiation levels. Rooftop solar installations continue to expand in urban centers like Jakarta and Surabaya (IESR, 2018). Indonesia, with 40% of the world's geothermal reserves, concentrates geothermal development in West Java, North Sumatra, and Sulawesi. Significant hydropower potential exists in Kalimantan, Sumatra, and Papua, with large rivers suitable for both small- and large-scale hydropower projects. The Java and Sumatra regions have abundant agricultural waste and municipal solid waste, ideal for biomass energy and waste-to-energy conversion (Erdiwansyah et al., 2024). Wind energy potential is also notable, particularly in the coastal regions in South Sulawesi and East Nusa Tenggara, which exhibit strong potential due to favorable wind speeds (Pambudi et al., 2025).

### 3.3.2 Economic feasibility and cost analysis of renewable resources

The economic feasibility of renewable energy technologies is essential for understanding Indonesia's transition to a low-carbon economy. This section evaluates the NPV and LCOE for solar PV, geothermal, hydropower, biomass, and wind energy, providing insights into their financial viability. NPV represents the total present value of investment and future operation and maintenance (O&M) costs over the project's lifetime, discounted to present value. It is calculated using Equation (2). The LCOE measures the average cost per kWh of electricity generated over the plant's lifetime and is calculated using Equation (3).

The initial investment costs presented in the economic analysis were estimated based on standardized or average global investment costs per megawatt (MW) and scaled to a hypothetical installed capacity of 1,000 MW (1 gigawatt) for each technology. This assumption is used for normalization purposes to enable direct comparison across different renewable technologies under uniform conditions. It does not reflect the exact scale of ongoing or planned projects in Indonesia. In practice, actual project sizes vary significantly depending on site potential, financing availability, and grid integration. Using a standardized benchmark ensures that the relative economic performance of technologies, measured through NPV and LCOE, can be compared transparently, while real-world deployment still requires project-specific feasibility assessments. This scaling assumption also allows cost estimates to be expressed in total USD rather than on a per-MW basis. The cost estimates are derived from reputable international sources and reflect typical project development conditions (IESR, 2025; IRENA, 2023). For solar PV, the assumed investment cost is USD 800,000 per MW, resulting in a total investment of USD 800 million for 1,000 MW. Geothermal energy projects, which involve costly exploration and drilling phases, are estimated at USD 2.5 million per MW, leading to a total cost of USD 2.5 billion. Hydropower projects are estimated at USD 2 million per MW (USD 2 billion total), while biomass-based systems are estimated at USD 1.8 million per MW (USD 1.8 billion). Wind energy projects are modeled with an investment cost of USD 1.5 million per MW, totaling USD 1.5 billion for 1,000 MW.

Annual operation and maintenance (O&M) costs are typically expressed as a percentage of the initial investment and vary by technology type. For this analysis, solar PV has an annual O&M cost of 1.5%, geothermal 2.0%, hydropower 1.0%, biomass 1.8%, and wind 1.2%. These values are informed by cost data from IRENA and relevant industry benchmarks (IRENA, 2023). The project lifetime is assumed to be 25 years for all technologies to standardize the LCOE and NPV comparisons. While actual lifespans may differ slightly (e.g., 20–30 years), 25 years is a commonly used assumption in policy and financial modeling. The discount rate used in the NPV and LCOE calculations is 8%, reflecting a typical rate applied in energy sector investment evaluations in emerging markets. This rate accounts for capital cost, inflation, and investment risks.

Annual energy output is based on typical capacity factors for each technology. For instance, solar PV is assumed to generate 1,500 MWh/year per MW installed capacity (capacity factor ~17%), wind 3,000 MWh/year (~34%), biomass 6,000 MWh/year (~68%), hydropower 4,000 MWh/year (~46%), and geothermal 8,000 MWh/year (~91%). These outputs reflect average performance observed in Southeast Asia and globally. Economic factors for each renewable energy source are summarized in Table 2.

Biomass and geothermal energy technologies exhibit the lowest LCOE, primarily due to their high-capacity factors and ability to provide reliable baseload power (Table 3). Geothermal energy stands out with an NPV of 3,033.74 million USD, making it particularly attractive for long-term energy planning because of its consistent output and operational stability. In contrast, PV technology, while having a lower NPV of 928.10 million USD and a relatively higher LCOE, continues to be a viable option due to ongoing cost reductions in PV modules and installation. Its scalability and ease of deployment make it well-suited for both urban and rural electrification efforts.

Hydropower, with an NPV of 2,213.50 million USD and a competitive LCOE, leverages Indonesia's abundant river systems, especially in regions like Sumatra and Papua, but still faces environmental and geographical limitations that may hinder large-scale development. Meanwhile, wind energy, although burdened with a higher LCOE due to intermittency, holds significant promise in coastal areas such as South Sulawesi and East Nusa Tenggara, where wind conditions are favorable.

To support a robust renewable energy transition, Indonesia should prioritize the cost-effective potential of biomass and geothermal sources while also scaling up solar PV and wind technologies to ensure a diversified and resilient energy mix. This transition requires strategic investments in infrastructure, strong regulatory frameworks, and continued technological innovation to drive sustainable and economically sound energy development.

### 3.3.3 Comparative analysis

A comparative evaluation of the BAU and low-carbon scenarios underscores the disparity between Indonesia’s current energy trajectory and the level of transformation required to align with its climate commitments. The low-carbon scenario nearly doubles the renewable energy

**Table 2.** Economic factors of renewable energy resources

| Technology | Initial investment cost (Million USD) | Annual O&M costs (Million USD) | Discount rate (%) | Project lifetime (Years) | Annual energy output (MWh) | Total present value (Million USD) |
|---|---|---|---|---|---|---|
| Solar PV | 800 | 12.0 | 8.0 | 25 | 1,500 | 928.10 |
| Geothermal | 2,500 | 50.0 | 8.0 | 25 | 8,000 | 3,033.74 |
| Hydropower | 2,000 | 20.0 | 8.0 | 25 | 4,000 | 2,213.50 |
| Biomass | 1,800 | 32.4 | 8.0 | 25 | 6,000 | 2,145.86 |
| Wind | 1,500 | 18.0 | 8.0 | 25 | 3,000 | 1,692.15 |

**Table 3.** NPV and LCOE

| Technology | NPV (Million USD) | LCOE (USD/kWh) |
|---|---|---|
| Solar PV | 928.10 | 0.058 |
| Geothermal | 3,033.74 | 0.036 |
| Hydropower | 2,213.50 | 0.052 |
| Biomass | 2,145.86 | 0.034 |
| Wind | 1,692.15 | 0.053 |

capacity by 2050 compared to the BAU pathway (Figure 2), clearly demonstrating the impact of deliberate policy interventions, technological advancements, and strategic investment mobilization.

The findings presented in the figure reveal the extent to which policy ambition and implementation may influence renewable energy outcomes. Under the BAU scenario, the rate of renewable energy deployment follows a relatively conservative growth pattern, constrained by existing regulatory frameworks and limited financial incentives. In contrast, the low-carbon scenario illustrates a significantly steeper growth curve, made possible by integrated and comprehensive policy reforms.

This divergence in projected outcomes carries important implications for Indonesia's ability to fulfill its NDCs under the Paris Agreement, which call for substantial reductions in greenhouse gas emissions by 2030. Additionally, it reflects the feasibility of achieving the goals articulated in the LTS-LCCR 2050, which envisions a decarbonized energy sector supported by robust renewable energy deployment. The analysis highlights the need for immediate and sustained action to close the gap between existing trends and desired targets. By prioritizing renewable energy expansion through forward-looking policies, fostering innovation in clean energy technologies, and catalyzing both public and private investment, Indonesia can significantly enhance its energy security, reduce dependence on fossil fuels, and build a more climate-resilient economy.

Indonesia's GHG emissions trajectory under the BAU scenario shows a gradual decline, primarily due to incremental improvements in energy efficiency and modest renewable energy integration. By contrast, the low-carbon scenario demonstrates a significant reduction in emissions due to aggressive deployment of renewable energy technologies and robust policy interventions.

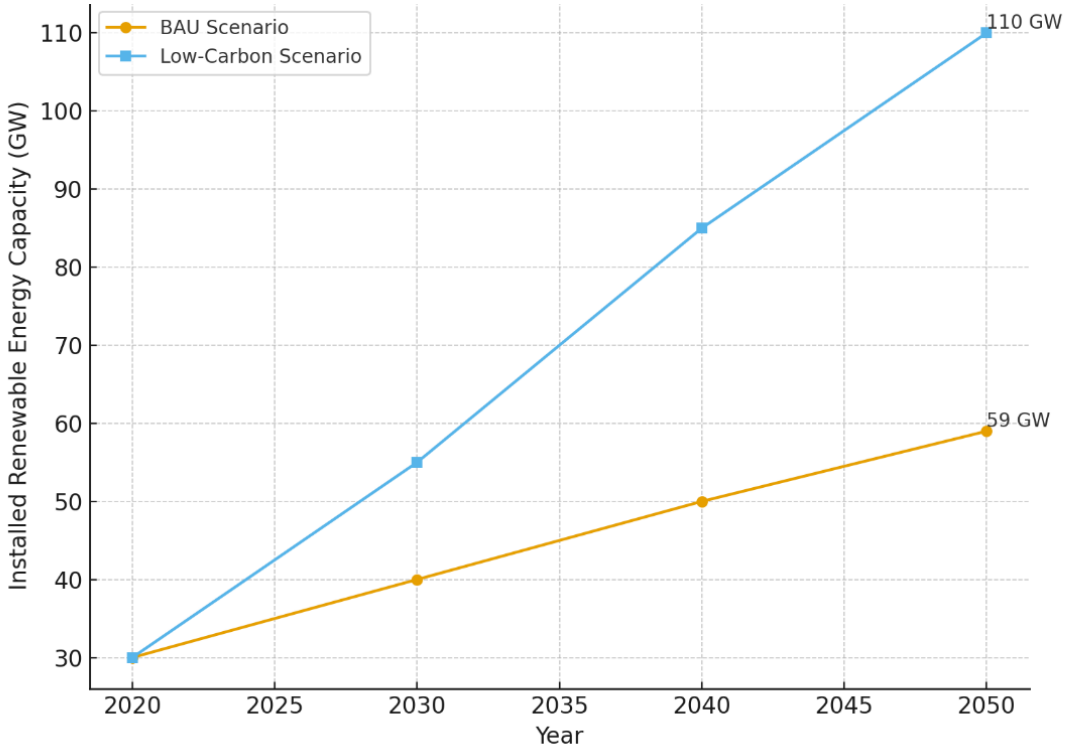


**Figure 2.** Projected renewable energy capacity growth in Indonesia (2020–2050)

As shown in Figure 3, Indonesia's GHG emissions under the BAU scenario are expected to decline slowly from about 600 million tonnes of $CO_2$ equivalent in 2020 to roughly 540 million tonnes by 2050. These gradual decreases indicates that if the country maintains with its current energy and policy approaches, which mostly focus on small improvements in energy use and limited growth in renewable energy, the progress remains limited. Looking closely at the numbers, there is a clear difference between the two paths. The BAU approach manages to cut emissions by 60 million tonnes over 30 years, which amounts to around 2 million tonnes less each year. In comparison, the low-carbon scenario cuts 300 million tonnes in the same period, averaging 10 million tonnes per year.

These results are highly important for Indonesia's efforts to meet its international commitments on climate action. Under the Paris Agreement, Indonesia aims to cut emissions by 29% on its own, and up to 41% if it gets international help, by the year 2030, compared to what it would emit under the BAU scenario. The strong reduction in the low-carbon scenario shows that Indonesia has strong potential to reach the 41% goal if it takes bold action now and receives adequate support.

Looking further ahead, this low-carbon scenario aligns with Indonesia's long-term plans for a low-carbon and climate-resilient future, as described in its LTS-LCCR 2050 strategy. This future includes greater deployment of renewable energy, enhanced energy efficiency, and a gradual shift away from fossil fuels. By 2050, following this path could help the country become more self-reliant in energy strengthening its preparedness to handle climate-related risks and changes.

To make this vision a reality, strong and sustained efforts are needed. This includes coherent government policies, international cooperation, and substantial investments in renewable energy projects. The rules and systems that manage energy markets must be updated to support clean technologies, and more research will be required to identify innovative solutions. Support from the international community, in both financial resources and technical expertise, will be critical in ensuring Indonesia can succeed in this transition. The data and trends clearly show that speeding up the shift to renewable energy is not only possible but also necessary. It's the key to cutting emissions, improving energy security, and building a stronger and greener economy for the future.

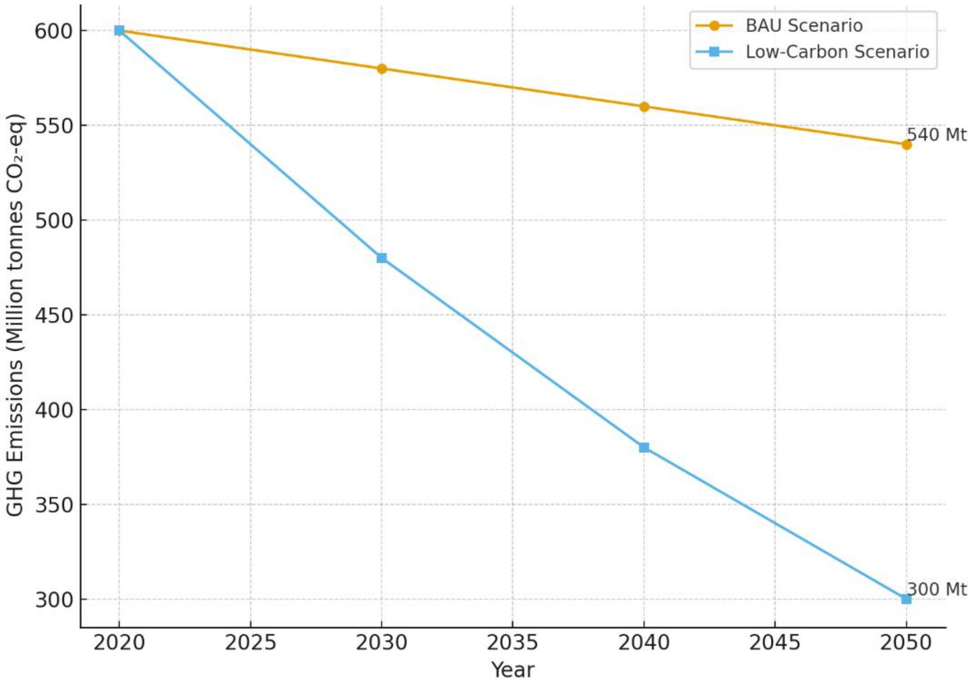


**Figure 3.** Projected GHG emissions in Indonesia (2020–2050)

The LCOE serves as a critical indicator for evaluating the cost-effectiveness of different renewable energy pathways. Under the BAU scenario, the slower pace of renewable energy adoption, limited investment in advanced technologies, and dependence on conventional grid infrastructure generally result in higher LCOE values (Table 4). This is largely due to smaller economies of scale, higher financing costs, and less optimized integration of renewables into the existing energy mix.

Conversely, the low-carbon scenario is characterized by rapid deployment of renewable energy technologies, enabling bulk procurement, standardized construction practices, and more efficient project execution. These factors lead to lower capital costs per MW, greater utilization rates, and improved capacity factors. Additionally, the integration of smart grid systems, energy storage, and supportive policy frameworks, such as feed-in tariffs, tax incentives, and concessional financing, contribute to significant reductions in LCOE across most technologies.

These values reflect the influence of more favorable financial terms, improved technology, and higher efficiency under the low-carbon scenario. For example, while solar PV has an estimated LCOE of $0.058/kWh under BAU conditions, it may fall to $0.040–0.045/kWh in the low-carbon scenario. Similar trends apply to wind, biomass, and hydropower, highlighting the importance of ambitious deployment strategies, as shown in Table 4.

Among the evaluated renewable energy technologies, biomass energy and geothermal energy emerge as the most economically viable options. This conclusion is drawn from their notably low LCOE, which reflects both high-capacity factors and the ability to provide reliable baseload power generation. Geothermal systems typically operate at capacity factors exceeding 90%, while biomass plants often exceed 65%, allowing them to produce energy continuously and efficiently. These characteristics reduce variability in output and enhance predictability in revenue streams, which are crucial for securing long-term financing and ensuring project bankability. Their high upfront costs are mitigated over time by strong operational performance and consistent energy delivery.

On the other hand, solar PV and wind energy also demonstrate increasingly competitive LCOE values. Despite being intermittent energy sources, they benefit from rapidly declining technology costs, modular scalability, and relatively short construction times. Technological advancements in panel efficiency, turbine design, and energy storage integration have significantly improved their economic outlook. For example, the LCOE of utility-scale solar PV has dropped dramatically in the past decade, positioning it as one of the lowest-cost energy sources in many regions. Similarly, onshore wind projects continue to expand due to favorable site conditions, particularly in Indonesia's coastal and island regions, and the ability to deploy systems relatively quickly.

Hydropower, while historically a cornerstone of renewable electricity generation, offers only moderate economic feasibility in the Indonesian context. Its LCOE remains competitive, especially for large-scale installations, due to long asset lifetimes and low O&M costs. However, hydropower development faces increasing geographical and environmental constraints. Many of the most accessible and economically viable river basins have already been developed, leaving future projects dependent on remote or ecologically sensitive areas. Additionally, large-scale hydropower often entails social and environmental trade-offs, such as displacement, deforestation, and alterations to river ecosystems, which may affect public acceptance and regulatory approval.

**Table 4.** Estimated LCOE comparison under BAU and low-carbon scenarios

| Technology | LCOE (USD/kWh) - BAU | LCOE (USD/kWh) - Low-carbon |
|---|---|---|
| Solar PV | 0.058 | 0.040–0.045 |
| Geothermal | 0.036 | 0.030–0.032 |
| Hydropower | 0.052 | 0.045–0.048 |
| Biomass | 0.034 | 0.028–0.030 |
| Wind | 0.053 | 0.038–0.042 |

### 3.3.4 Sensitivity analysis

A sensitivity analysis was conducted to evaluate how variations in policy support, technology costs, and demand growth impact the NPV of different renewable energy technologies. This analysis provides insights into which factors most significantly influence investment returns in Indonesia's renewable energy sector. The sensitivity analysis indicates that decreased technology costs have the most significant impact on NPV across all renewable energy technologies. As shown in Table 5, this effect is particularly pronounced in geothermal and biomass systems, which are highly capital-intensive. Therefore, reductions in upfront investment costs lead to substantial improvements in project viability and highlight the critical role of ongoing technology cost declines.

Policy support also plays an important role, especially for technologies such as solar PV and wind energy. These systems tend to be more sensitive to financial incentives, including subsidies, tax breaks, and preferential tariffs. Enhanced policy support moderately improves NPV for these technologies by offsetting operational and capital expenses, thus strengthening their competitiveness in the energy market.

Furthermore, demand growth contributes positively across all technologies. An increase in electricity demand leads to higher energy sales, translating into greater revenues and improved returns on investment for renewable projects. The sensitivity analysis shows that technology cost reductions and robust policy frameworks are the two most critical levers for enhancing the economic attractiveness of renewable energy investments in Indonesia. Strategic government interventions, such as capital subsidies, investment tax credits, and technology-specific incentives, paired with favorable market dynamics, remain essential to accelerating Indonesia's transition to a low-carbon and sustainable energy future.

### 3.3.5 Challenges and opportunities for renewable energy transition

Indonesia's transition to a renewable energy-driven economy faces several significant challenges that hinder the pace of deployment and integration. One of the primary obstacles is regulatory barriers. Inconsistent and fragmented regulations across national and regional levels create uncertainty for investors and developers. Complex licensing procedures and bureaucratic delays further slow project development, particularly for decentralized energy systems. Additionally, policy reversals and unclear feed-in tariffs discourage long-term investment in renewable energy projects.

Infrastructure limitations also pose a major challenge. In many remote and rural areas, limited grid infrastructure restricts the integration of variable renewable energy sources such as solar and wind. The aging national grid system struggles to accommodate intermittent power without significant upgrades, including the adoption of smart grid technologies.

Financing constraints further complicate progress. High upfront capital costs and limited access to affordable financing present major hurdles, especially for small and medium enterprises. Perceived investment risks, exacerbated by policy uncertainty and a lack of financial guarantees, further deter private sector involvement.

**Table 5.** Sensitivity analysis for in-policy support, technology costs, and demand growth

| Technology | Increased policy support (Million USD) | Decreased technology cost (Million USD) | Increased demand growth (Million USD) |
|---|---|---|---|
| Solar PV | 1,020.91 | 1,160.13 | 1,020.91 |
| Geothermal | 3,337.11 | 3,792.18 | 3,337.11 |
| Hydropower | 2,434.85 | 2,766.88 | 2,434.85 |
| Biomass | 2,360.45 | 2,682.33 | 2,360.45 |
| Wind | 1,861.37 | 2,115.19 | 1,861.37 |

Despite these challenges, Indonesia holds substantial opportunities to accelerate its renewable energy transition through targeted actions. Policy reforms are essential, including efforts to strengthen regulatory frameworks by simplifying licensing processes, setting clear renewable energy targets, and introducing market-based mechanisms such as carbon pricing. Incentives such as tax benefits, feed-in tariffs, and support for public-private partnerships are also crucial for driving growth.

Technological innovations offer another pathway forward. Advancements in smart grid systems and energy storage could improve grid reliability and better manage the variability inherent in renewable energy generation. Promoting research and development for localized solutions, particularly in solar photovoltaics, biomass, and mini-hydro systems, can help adapt technologies to Indonesia's specific needs. Finally, greater stakeholder collaboration is crucial. Encouraging partnerships among the government, the private sector, and international development agencies can help mobilize investment and facilitate technology transfer. Engaging local communities and small enterprises in decentralized renewable energy initiatives also helps enhance social acceptance and foster a sense of ownership, supporting long-term sustainability.

Beyond regulatory barriers, Indonesia's renewable energy transition is further constrained by broader political, social, and institutional factors. The electricity sector remains heavily centralized under PLN, which holds a near-monopoly over generation and distribution. This dominance often discourages private investment and slows innovation, as Independent Power Producers (IPPs) face limited bargaining power in Power Purchase Agreements (PPAs). Additionally, fragmented regulations across national and regional levels create policy uncertainty, while frequent changes in ministerial decrees undermine investor confidence. The persistence of fossil fuel subsidies, particularly for coal, diesel, and electricity tariffs, further distorts the market by making renewables less competitive in the short term.

On the social dimension, community acceptance and energy justice issues are critical. Large-scale projects, such as hydropower and geothermal, have occasionally faced opposition due to land acquisition, displacement, and environmental impacts. These conflicts highlight the importance of ensuring procedural and distributive justice, where local communities are not only consulted but also share the benefits of renewable energy development. Strengthening participatory planning, revenue-sharing mechanisms, and capacity-building at the community level can improve social acceptance and accelerate the just energy transition in Indonesia.

While this study provides valuable insights into the techno-economic feasibility of renewable energy pathways, it does not fully capture social and environmental externalities. Factors such as land-use competition, potential displacement of communities, biodiversity impacts, and water resource implications were beyond the scope of this analysis. These dimensions are highly relevant for Indonesia, particularly in the development of large-scale hydropower, geothermal, and bioenergy projects. Future research should therefore integrate environmental and social impact assessments alongside techno-economic modeling to provide a more comprehensive evaluation of renewable energy pathways.

## 4 Conclusions and recommendations

This paper provides a comprehensive analysis of renewable energy pathways in Indonesia's LTS-LCCR 2050. The results highlight the critical role of renewable energy in reducing GHG emissions, enhancing energy security, and supporting sustainable development goals. Scenario-based projections demonstrate that under a low-carbon scenario, Indonesia can nearly double its renewable energy capacity by 2050 compared to the BAU trajectory while reducing GHG emissions by up to 50%. This reduction will play a vital role in achieving the nation's NDC targets and broader climate resilience goals.

The economic feasibility analysis reveals that biomass and geothermal energy offer the lowest LCOE, making them highly attractive due to their high-capacity factors and ability to provide baseload power. Solar PV and wind technologies show increasingly competitive LCOEs, benefiting from declining capital costs and scalable deployment potential. Hydropower, while cost-effective in many cases, faces site and environmental limitations that may constrain future expansion.

The comparative analysis between BAU and low-carbon scenarios indicates that policy interventions, such as investment incentives and improved grid infrastructure, can significantly lower LCOEs across all technologies. Sensitivity analysis confirms that investment cost and capacity factor are the most influential variables affecting both NPV and LCOE. Technological advancement, cost reduction, and favorable financing conditions are therefore essential for unlocking the economic viability of renewable projects. Furthermore, the inclusion of strategic policy incentives, including tax exemptions, feed-in tariffs, and concessional loans, is crucial in stimulating investment and achieving scale.

To support Indonesia's transition to a low-carbon energy future, policy and investment actions should be prioritized across short-, medium-, and long-term horizons. In the short term (by 2030): strengthen policy incentives such as tax credits, feed-in tariffs, and concessional financing; reduce fossil fuel subsidies; and accelerate deployment of rooftop solar and mini-grid solutions, particularly in underserved regions. In the medium term (2030–2040): expand large-scale renewable projects in geothermal, hydropower, and biomass; modernize transmission infrastructure with smart grid technologies; and establish robust carbon pricing mechanisms to align with climate goals. International climate finance and concessional loans remain critical during this phase to reduce investment risks and mobilize private capital. In the long term (2040–2050): achieve deep decarbonization of the power sector by integrating high shares of solar and wind with advanced energy storage and carbon capture technologies. Technology transfer and collaborative research and development partnerships with international institutions are essential to ensure Indonesia can access next-generation innovations while strengthening local manufacturing capacity.

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