Optimization of Renewable Energy Integration in Power Systems for Clean Energy Transition

Van Bastian Situmorang, Zuraidah Tharo, Parlin Siagian

Abstract

Global climate change caused by increasing greenhouse gas emissions has prompted the world to transition toward a sustainable clean energy system. Indonesia, as a developing country with rapidly growing electricity demand, faces significant challenges in realizing this energy transition. The national electricity system remains heavily dependent on fossil fuels, particularly coal, which contributes substantially to carbon emissions. This study aims to analyze the potential, challenges, and strategies for optimizing the utilization of renewable energy within Indonesia's power system. The research applies a qualitative descriptive method through an extensive literature review from scientific journals, reports, and official publications. The results indicate that Indonesia possesses abundant renewable energy potential, including solar energy of 207.8 GWp, hydropower of 75 GW, wind energy of 60.6 GW, and geothermal energy exceeding 28 GW. However, the current utilization rate remains low, only around 14% of the total national energy mix. The main barriers include limited infrastructure, high investment costs, and uncompetitive regulatory frameworks. To overcome these challenges, optimization strategies should focus on strengthening policy and regulatory support, implementing smart grid and energy storage technologies, and fostering collaboration between government, industry, and society. With these integrated efforts, Indonesia can accelerate the transition toward a clean, efficient, and sustainable electricity system to achieve the Net Zero Emission target by 2060.

Keywords: Renewable Energy, Clean Energy Transition, Power System, Smart Grid, Net Zero Emission

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Introduction

Energy and environmental issues have become one of the most pressing global challenges of the 21st century. The primary issue facing the world today is climate change, the impacts of which are increasingly evident, from rising global temperatures and rising sea levels to the increasing frequency of hydrometeorological disasters. The Intergovernmental Panel on Climate Change (IPCC) report confirms that global warming exceeding the 1.5°C threshold will pose serious risks to the sustainability of human life and ecosystems in various parts of the world[1]. One of the largest contributors to accelerating climate change is greenhouse gas emissions from human activities, particularly the energy sector. The energy sector is recorded as the leading contributor to global carbon dioxide (CO_2) emissions. According to data from the International Energy Agency (IEA), more than 70% of total global CO_2 emissions come from the energy sector, particularly from the combustion of fossil fuels such as coal, oil, and natural gas[2]. The world's centuries-long dependence on fossil fuels has indeed driven economic growth and industrialization, but it has also left a significant environmental footprint. This makes the clean energy transition a global agenda that cannot be postponed any longer.

International awareness of the urgency of the energy transition is reflected in various global agreements and commitments. One such agreement is the 2015 Paris Agreement, which emphasizes the importance of efforts to keep global temperature rise well below 2°C, with an ideal target of no more than 1.5°C.[3] To achieve this, almost all countries have confirmed their commitment to the Net Zero Emission (NZE) target by 2050.[2][4] This target requires each country to gradually reduce its dependence on fossil fuels, increase energy efficiency, and accelerate the use of renewable energy as its primary source. In this context, renewable energy is seen as the primary solution for the future of the global energy system.[3][4] Utilizing solar, wind, hydro, biomass, and geothermal energy is considered capable of providing clean, sustainable, and more environmentally friendly energy than fossil-based energy. Furthermore, global trends indicate that the cost of renewable energy technologies is increasingly competitive, particularly solar and wind energy, which have seen price drops of more than 80% over the past two decades.[5] This transformation reinforces the urgency and opportunity for all countries to optimize the use of renewable energy as part of the global electricity system.

At the national level, Indonesia faces equally complex challenges in energy supply. Economic growth and population growth directly drive increased demand for energy, particularly electricity, a basic human need and a key pillar of industrial activity. Data from the Ministry of Energy and Mineral Resources (ESDM) shows that national electricity consumption continues to increase, with an average annual growth rate of around 4.5%.[6] This increase reflects the significant need for electricity to support national development, across the residential, commercial, and industrial sectors. However, the supply of this energy remains heavily reliant on fossil fuels. More than 60% of Indonesia's electricity is still coal-based, with oil and natural gas remaining as the other primary sources.[6][3] This high dependence on fossil fuels not only creates environmental problems through high greenhouse gas emissions, but also creates vulnerabilities in terms of energy security, given the decreasing availability of fossil fuels and causing energy prices on the global market. In an effort to reduce dependence on fossil fuels and encourage the use of clean energy, the government has set a target in the National Energy General Plan (RUEN). This target is to achieve a renewable energy mix of 23% by 2025. However, the realization of this achievement as of 2023 is still around 14% of the total national energy mix.[7] The significant difference between the target and the actual results indicates a gap that must be addressed immediately through more targeted strategies and policies, including in the electricity sector, which is the backbone of the national energy transition.

This requires supporting technologies such as energy storage systems (batteries) and smart grids to ensure electricity availability and optimal distribution. Furthermore, challenges arise from infrastructure and costs. Investment in renewable energy generation and transmission and distribution networks capable of accommodating new electricity supplies remains relatively expensive, often presenting obstacles for developers and investors.[5] Data from the Ministry of Energy and Mineral Resources indicates that Indonesia's installed renewable energy capacity will only reach around 13–14 gigawatts (GW) by 2023, out of a total national electricity capacity of over 80 GW. This means that renewable energy's contribution to the electricity system remains relatively small compared to the dominance of fossil-fueled power plants.[7] This condition is also exacerbated by the limitations of regulations, licensing, and electricity selling price schemes that are considered less attractive for investors to participate more in the development of renewable energy in the electricity sector.

Although the contribution of renewable energy to the national electricity system is still relatively small, Indonesia's potential is actually enormous and holds great promise for development. The Ministry of Energy and Mineral Resources (ESDM) notes that Indonesia has solar energy potential of approximately 207.8 gigawatt peak (GWp), hydropower of 75 gigawatts (GW), and wind power of approximately 60.6 GW across various regions (ESDM, 2023).[3] Furthermore, Indonesia's geothermal potential is abundant, with estimated reserves exceeding 28 GW, making it one of the countries with the largest geothermal resources in the world. If this potential can be optimally utilized, Indonesia will not only be able to reduce its dependence on fossil fuels but also have the potential to become a significant player in clean energy development in Southeast Asia.

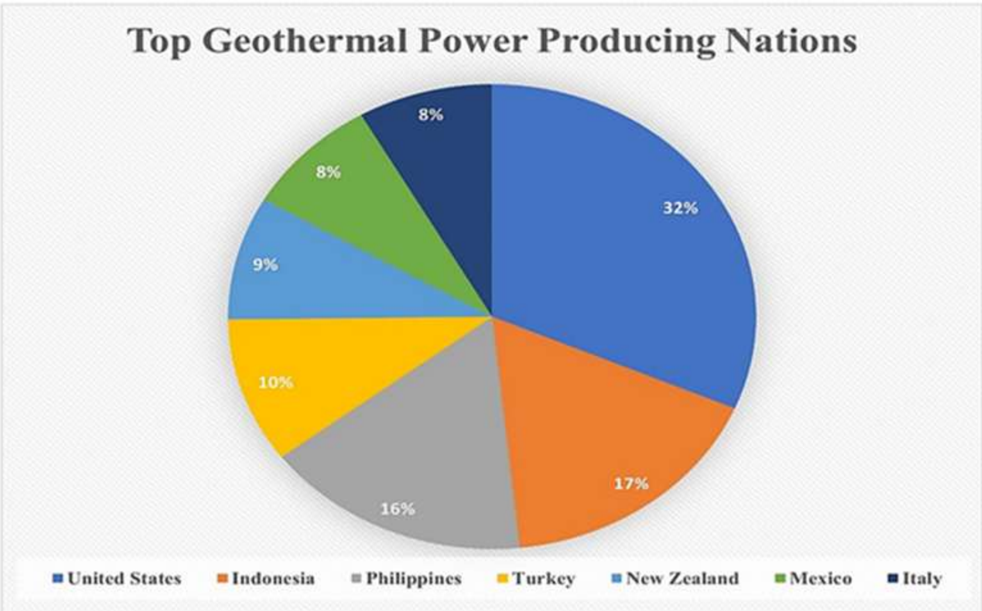

Figure 1. Geothermal Energy Opportunities[2]

However, realizing this enormous potential still faces various challenges. Technically, the availability of supporting infrastructure to integrate renewable energy generation into the national electricity grid remains very limited.[8][9] Energy storage technologies, such as large-capacity batteries, needed to address intermittency issues, are also still expensive and underutilized. Furthermore, the initial investment costs for renewable energy power plants are relatively high compared to fossil-fueled power plants, making investors more cautious about investing.[7] Another equally significant challenge is the limited regulatory and incentive policies. Renewable energy tariffs are often considered less competitive, while project permitting is still considered complicated and time-consuming, ultimately slowing the penetration of clean energy into the national electricity system.[5]

The stark gap between the vast potential of renewable energy and the low utilization rate in the national electricity system indicates a problem that must be addressed immediately. Indonesia possesses abundant renewable energy resources, but their utilization remains far from the established targets, thus preventing it from optimally contributing to the clean energy transition.[1] This raises fundamental questions about how strategies for optimizing the use of renewable energy can be implemented to strengthen the electricity system while supporting the national energy transition agenda towards more sustainable energy.[10] In an effort to answer these questions, this research will examine various influencing factors, starting from technical aspects related to network stability and storage technology, regulatory and policy aspects that support investment, economic aspects related to costs and financing schemes, to social aspects that include public acceptance and changes in energy consumption patterns.[5] Thus, this study aims to provide a comprehensive overview of efforts to optimize the use of renewable energy in the electric power system, so that it can become an important foundation for realizing a clean energy transition in Indonesia.

Literature Review

The transition from a fossil fuel-based power system to a renewable energy (RE)-based power system is a crucial step in addressing climate change and achieving global decarbonization targets.[11] As stated by Kabeyi and Olanrewaju, the sustainability of the electric power system is not only a matter of replacing sources, but also relates to technical, economic, social, institutional/political and environmental dimensions.[8] In this context, the electric power system that supports Renewable Energy must have sufficient flexibility and reliability to cope with the variability of renewable generation such as solar and wind.[12]

The updated paper by Yu, You & Zhou discusses that optimization models and resolution techniques are an important part of decision making related to Renewable Energy systems from investment, operation, to maintenance.[13][14] With increasing penetration of Renewable Energy, challenges such as variability and uncertainty become increasingly significant.

Specific example: the paper on Optimal Power Flow in Renewable-Integrated Power Systems highlights that the integration of renewable sources complicates power flow control, requiring adaptive OPF strategies.[14] Thus, to optimize the use of Renewable Energy, it is not enough to just increase capacity, but also requires optimization of network systems, energy storage, and flexible control.

Giedraityte et al. present a comprehensive review of hybrid renewable systems (HRES) that combine various renewable energy sources such as: solar, wind, biomass, geothermal as well as energy storage.[15] The study shows that meta-heuristic algorithms such as NSGA-II, GWO, and MILP models are widely applied for HRES optimization in economic, technical, and environmental aspects. This is relevant to the optimization of clean transition power systems, where HRES can play a crucial role in improving system reliability and efficiency.[16] This is supported by research by Tharo et al., which in Indonesia shows the combination of solar and wind power as a solution for providing cheap and environmentally friendly energy, supporting the national clean energy transition agenda.[17] In addition, solar energy is one of the most potential renewable energy sources in Indonesia. Siagian et al.[18]

Ukoba (2024) presents a state-of-the-art review of the application of artificial intelligence (AI) in renewable energy systems, including the areas of forecasting, energy storage management, and smart grid control.[19] With increasing load dynamics (e.g., data centers, EVs) and weather-dependent supply, AI integration is becoming increasingly important to achieve operational efficiency and system stability.[11]

Another study by Siagian et al developed a method of increasing solar panel power using a light concentrator made of aluminum foil to increase energy absorption efficiency.[18]

Bamisile (2024) reviewed optimization techniques specific to energy storage systems and HRES, emphasizing that the system value of Renewable Energy, such as curtailment, peak shaving, and grid-storage-generation integration, must be taken into account.[20][21] This approach is important when designing business and technical models that ensure RE investments not only add capacity, but improve overall system performance.

While much technical research is needed, national implementation requires synchronized policies and regulations. As a case study in Indonesia, the RUPTL (Regional Electricity and Power Plant) and reports from national utility institutions indicate that increasing renewable energy capacity must be accompanied by network strengthening and green financing. In this literature, Rahayu (2025) shows that the integration of AI technology and smart networks in RE systems increases operational reliability and efficiency, which is part of the national strategy for renewable energy transition.[22] Strengthened by Siagian P's research, regarding the utilization of wind power in coastal areas after the COVID-19 pandemic, it strengthens that the decentralization of renewable energy generation can support the MSME and tourism sectors, in line with the green economy agenda.[23]

The literature above shows that optimizing renewable energy utilization requires a multidisciplinary approach, involving sensor technology, artificial intelligence, mathematical optimization, and clean energy transition policies. The combination of technical innovations (such as OPF and HRES) and national policies (RUPTL, JETP) is key to accelerating the transformation of an efficient and sustainable electric power system.

Research Method

This research uses a descriptive qualitative approach to analyze strategies for optimizing renewable energy utilization in the national electricity system. This approach was chosen because the research focuses on interpreting phenomena, policy dynamics, and technical and economic factors influencing the clean energy transition process, rather than on testing statistical relationships or quantitative calculations.

The data used in this study is secondary data, obtained through a search of scientific literature, reports from national and international institutions, and policy and regulatory documents related to renewable energy. Data sources include publications from the Ministry of Energy and Mineral Resources (ESDM), the State Electricity Company (PLN), the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), and scientific articles from accredited national journals and reputable international journals. Secondary data was selected because it can provide a comprehensive picture of the development of national and global energy systems.

Data collection techniques were carried out through library research and document analysis, with the following steps: (1) identifying literature relevant to the research topic; (2) selecting sources based on credibility, year of publication, and relevance to the study variables; and (3) extracting core information from each document studied.

Next, the data was analyzed using qualitative descriptive analysis, which included data reduction, theme categorization, interpretation, and conclusion drawing. The collected data were grouped into four main analysis categories: technical, economic, policy, and social aspects. The patterns and relationships between aspects are then interpreted to formulate strategies for optimizing the use of renewable energy in the electric power system.

The results of the analysis are used to formulate strategic recommendations that support the acceleration of the clean energy transition in Indonesia, taking into account implementation feasibility, infrastructure readiness, financing sustainability, and social acceptance in the context of the national electricity system.

The research procedure is illustrated in the following flowchart:

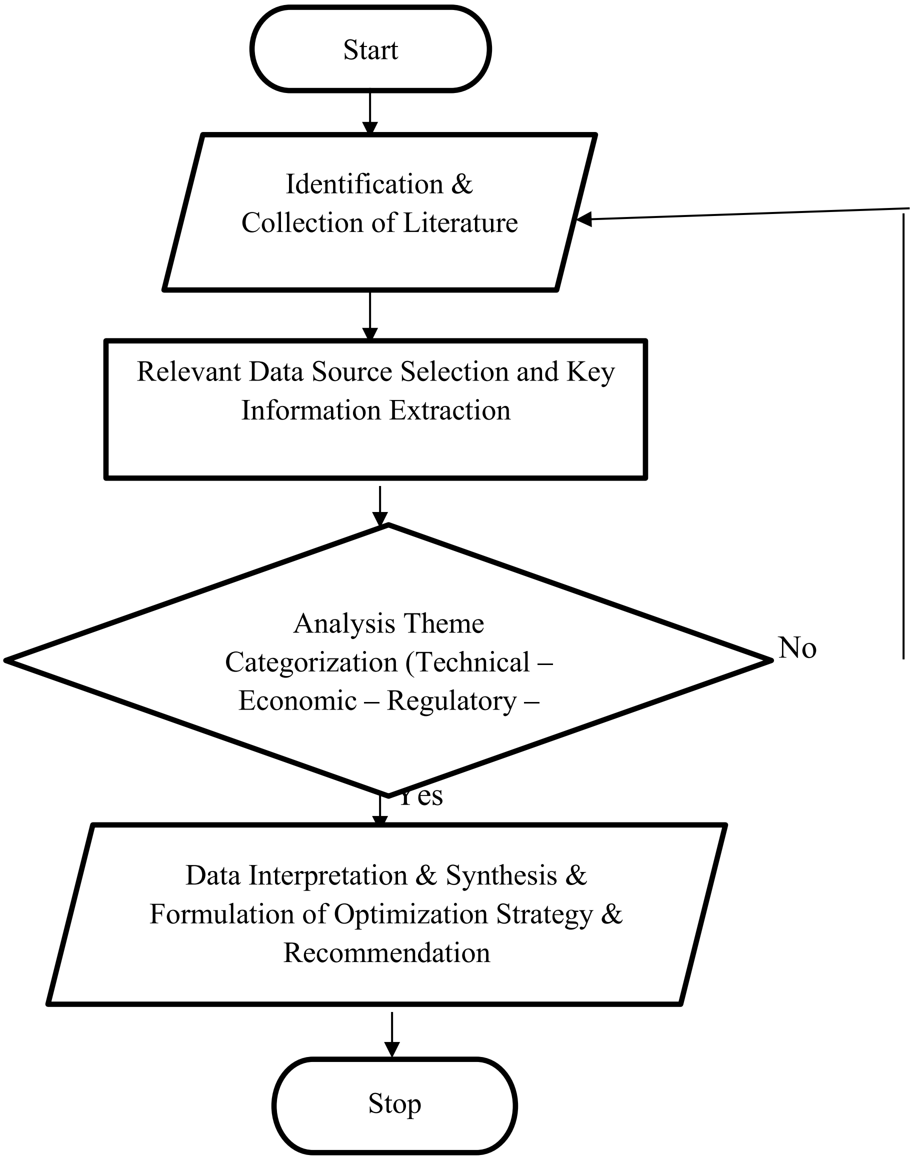

Figure 2. Flowchart System

Results And Discussion

4.1 Actual Conditions of Renewable Energy Utilization in Electric Power Systems

Despite Indonesia's enormous renewable energy potential, its utilization in the electricity system remains relatively low. Installed renewable energy generation capacity in 2023 is projected to be only around 13–14 gigawatts (GW) out of a total national capacity of over 80 GW, and the renewable energy mix has only reached around 14%, well below the 23% target by 2025. The high dependence on coal (over 60% of electricity supply) indicates that the energy transition is still in its early stages and requires more strategic and measured acceleration. This situation highlights the gap between potential energy sources and their actual utilization in the national electricity sector.

Figure 3. Renewable Energy Projects in Indonesia [5]

4.2 Challenges of Integrating Renewable Energy into Electric Power Systems

Renewable energy integration faces several major obstacles, some of which can be seen in the following table:

Table 1. Challenges of Integrating Renewable Energ

Aspect	**Challenges**	**Impact**
Technical	Solar & wind output variability; energy storage limitations	Risk of network instability, supply fluctuations
Economy	High initial investment costs; long-term returns	Investors tend to choose fossil fuels which provide a quicker return on investment.
Regulations	Layered licensing, feed-in tariff policy is not yet competitive	Renewable energy projects are progressing slowly
Social	Public acceptance is not yet evenly distributed; dependence on fossil fuel subsidies	Minimal changes in energy consumption patterns

The variability and uncertainty of solar and wind supply necessitate smart grid support and large-capacity energy storage systems. Furthermore, unattractive financing schemes and complex permitting processes slow the penetration of large-scale renewable energy projects.

4.3 Opportunities for Optimizing Electric Power Systems in the Energy Transition Period

Despite significant challenges, several strategic opportunities can be exploited:

1. The ongoing decline in the cost of solar panels and wind turbines opens up opportunities for the implementation of rooftop solar power plants, floating solar power plants, and local-scale wind power plants.
2. Hybrid Renewable Energy Systems (HRES) can improve system reliability through a combination of energy sources (e.g., solar, wind, and batteries).
3. The application of artificial intelligence (AI) in load and weather forecasting can improve operational efficiency, stability, and power planning.
4. Industrial decarbonization and transportation electrification (EVs) are driving increased demand for environmentally friendly electricity.

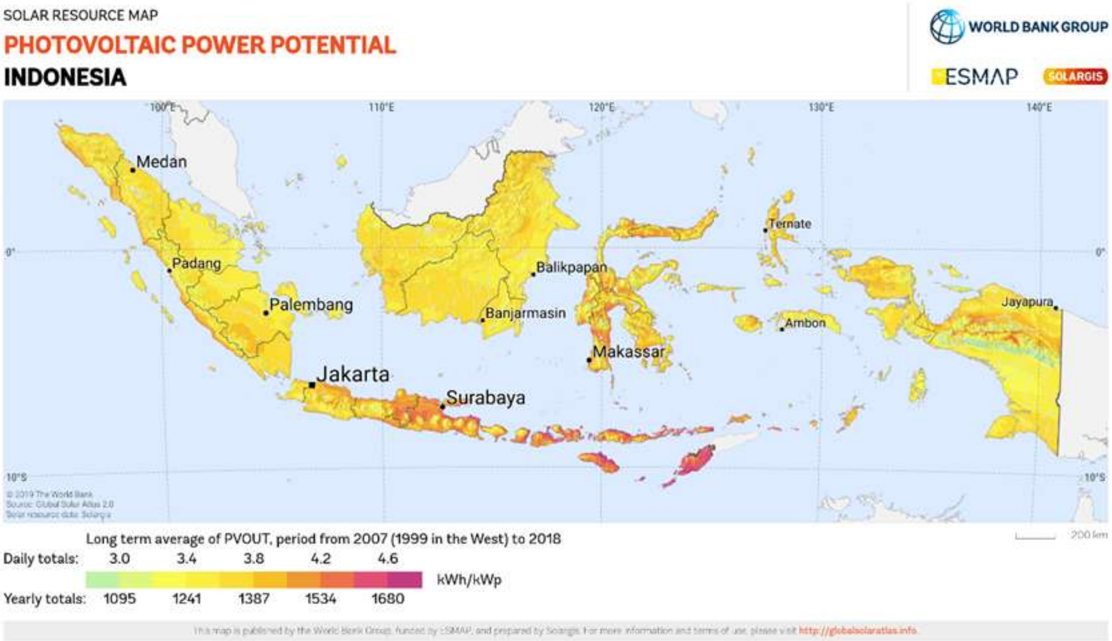

Figure 4. Solar Energy Potential in Indonesia [5]

These steps support the development of a flexible, adaptive and sustainable energy system.

4.4 Renewable Energy Utilization Optimization Strategy

Based on the analysis results, the main strategies that can be applied in renewable energy integration are listed in the table below:

Table 2. Renewable Energy Integration Optimization Strategy

Strategy	Implementation Direction	Long Term Impact
Network Infrastructure Strengthening	Grid modernization, smart metering, energy storage	Supply stability increases
Policy Reform and Incentives	Competitive feed-in tariffs, green financing, simplification of permits	Investor interest has increased significantly

Decentralization of Renewable Generation	Rooftop solar power plants, village microgrids, coastal wind power plants	Local energy independence increases
Integration of AI and Digital Systems	Load and weather prediction, power plant operation optimization	System efficiency increases
Increasing Public Education and Awareness	Clean energy consumption campaign	Social acceptance of the energy transition is strengthening

By combining these technical and policy strategies, Indonesia has the potential to accelerate the achievement of its sustainable clean energy transition targets.

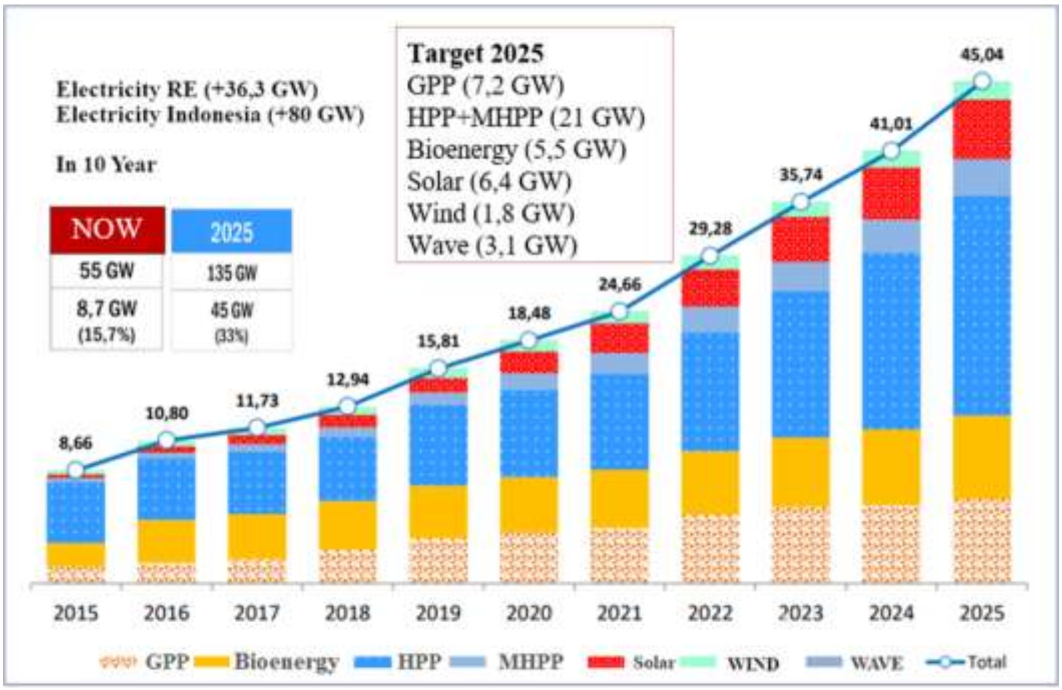

Figure 5. Graph of Installed Renewable Energy Capacity by Category in Indonesia[7]

The following data shows the results of Renewable Energy (ET) Integration in Indonesia's electricity system:

Table 3. Renewable Energy Integration in Indonesia

No	Renewable Energy Integration Indicator	Values / Achievements	System Impact Description	Source
1	Installed Capacity of Renewable Energy (2023)	13,15 GW	Shows that the portion of renewable energy is still low compared to the total of ±80	Kementerian ESDM, 2023

			GW of national power generation.	
2	Renewable Energy Mix (2023)	13,09%	Still below the 2025 RUEN target (23%) → requires acceleration of integration into the grid	Handbook of Energy Statistics ESDM, 2023
3	Cirata Floating Solar Power Plant (Inaugurated 2023)	192 MWp / 145 MWac	Contributes ±245 GWh/year & reduces ±214 thousand tons of CO_2/year	PLN & Masdar, 2023
4	PLN Customer Rooftop Solar Power Plant (Early 2024)	538 MWp (10.882 customers)	Contribution of energy decentralization & reduction of system peak loads	Direktorat EBTKE, 2024
5	Renewable Energy Integration Project by PLN (2024)	37 Project in 18 Provinsi	Improving transmission & substation reliability to absorb new Renewable Energy	PLN, RUPTL 2021–2030
6	Renewable Energy Addition Plan 2025–2034	+42,6 GW (Surya ±17,1 GW)	VRE penetration focus → requires flexibility and energy storage systems	RUPTL PLN 2021–2034
7	Application of Energy Storage System (BESS/ESS)	At the implementation roadmap stage	Key solutions for grid stability facing solar & wind variability	IESR & PLN Outlook, 2024
8	Reduction of TKDN Requirements for Solar Power Plants (2025)	Reduced to 20%	Accelerate investment & procurement of large-scale solar modules	Regulation of the Minister of Industry, 2024

Conclusion

The utilization of renewable energy in Indonesia's electricity system is currently showing positive developments, but it is not yet optimal. Although Indonesia has enormous renewable energy potential, its utilization rate is still relatively low, with its contribution to the national energy mix only reaching around 13–14%, still far from the target of 23% by 2025. This condition is influenced by several key obstacles, including the variability of renewable energy supply that requires a flexible electricity grid system, high initial investment costs, licensing complexity, and limited economic incentives and sustainable policy support.

The analysis shows that accelerating renewable energy integration can be achieved through strengthening electricity grid infrastructure, implementing energy storage systems, integrating artificial intelligence into power system management, and decentralizing community-based energy generation such as rooftop solar power plants and microgrids. Furthermore, policy reforms and the provision of green financing schemes play a crucial role in increasing investment appetite and encouraging private sector participation.

Thus, optimizing renewable energy utilization requires not only technical innovation but also adaptive policy approaches, multi-stakeholder collaboration, and increased public awareness of the importance of a clean energy transition. Implementing this strategy is believed to support the achievement of national decarbonization targets, strengthen energy security, and realize a sustainable and environmentally friendly electricity system.

Optimizing the use of renewable energy in Indonesia's electricity system requires strengthening regulatory, economic, technical, and social aspects in an integrated manner. Efforts to accelerate renewable energy integration depend not only on increasing generating capacity but also on adapting the electricity grid system, financing schemes, and market mechanisms to support power system flexibility and reliability.

1. Regulation and Governance
    - Simplifying renewable energy project licensing through a one-stop service mechanism with clear processing time standards.
    - Establishing consistent and sustainable policies, including price certainty (PPA) and grid integration regulations, to encourage a stable investment climate.
    - Establishing a Renewable Energy Integration Task Force across ministries, PLN, and local governments to synchronize network governance and planning.
2. Financing and Economic Incentives
    - Strengthening green financing schemes, such as green bonds, credit guarantees, and fiscal incentives for developers.
    - Implementing value-based tariff systems, such as feed-in premiums for utility-scale projects and stable net billing for rooftop solar power plants.
    - Reducing investment barriers through gradual flexibility of local content (TKDN) requirements based on the readiness of the national industry.
3. Strengthening Electric Power System Infrastructure
    - Modernizing the electricity grid through the implementation of smart grids, smart metering, and dynamic line rating to improve system reliability.
    - Developing the capacity of energy storage systems (ESS/BESS) and pumped hydro as flexible solutions to address solar and wind energy variability.
    - Strengthening grid reinforcement in regions with high renewable energy potential, such as East Nusa Tenggara (NTT), West Nusa Tenggara (NTB), Sulawesi, and West Sumatra.
4. Decentralization and Local Empowerment
    - Development of rooftop solar power plants, village microgrids, and community-scale renewable energy generators to increase energy independence and equitable electricity access.
    - Education programs and increased public literacy regarding the use of clean energy and the benefits of energy savings.

- A community-based energy governance model based on community ownership to encourage sustainable operations and maintenance.

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