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Role of Solar Photovoltaic Energy in GHG Emission Reduction within Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience 2050

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ABSTRACT

Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050) outlines ambitious goals for achieving a low-carbon and climate-resilient future, with solar photovoltaic (PV) energy playing a pivotal role. This paper explores the pathways, contributions, and challenges associated with achieving the target of 113 GW of installed solar PV capacity by 2050. Using a comprehensive methodology, the study examines solar energy potential, trends in PV deployment, greenhouse gas (GHG) emission reductions, and scenarios for target achievement. Findings highlight that transitioning to solar PV could reduce GHG emissions by approximately 794.87 million tons of CO_2 annually by replacing coal-based electricity. Three deployment scenarios are analyzed: constant growth, gradual ramp-up, and aggressive early deployment, each presenting unique challenges and opportunities. Key barriers include financial constraints, technical limitations, regulatory hurdles, and public acceptance issues. The study concludes that achieving the target requires strong policy frameworks, significant investments, and technological innovation. Solar PV has the potential to transform Indonesia's energy sector, contributing to national climate goals and sustainable development.

Keywords: Solar Photovoltaic Energy, Greenhouse Gas Reduction, Low Carbon Strategy, Renewable Energy Deployment, Indonesia Energy Transition

JEL Classifications: Q42, Q56, L94

1. INTRODUCTION

Climate change is widely acknowledged as one of the most intricate, multifaceted, and serious threats facing humanity. Under the principle of common but differentiated responsibilities and respective capabilities outlined in the United Nations Framework Convention on Climate Change (UNFCCC) Convention, each country's response to this challenge is shaped by its capacity to adapt to or build resilience against the impacts of a changing climate. At the same time, nations contribute to global efforts to reduce greenhouse gas emissions, as reflected in their Nationally Determined Contributions (NDCs) (UNFCCC.INT, 2024). In alignment with the Paris Agreement, countries are encouraged to articulate a long-term climate strategy that envisions a transition toward low greenhouse gas emissions over the next half-century (Government of Indonesia, 2021).

Many developed and developing countries have set ambitious climate targets to mitigate the impacts of global warming. The European Union, for example, aims for climate neutrality by 2050 and a 55% greenhouse gas emission reduction by 2030 compared to 1990 levels (European Commission, 2019). The United States has set a goal of achieving net-zero emissions economy-wide by 2050 (Binsted et al., 2024). China, the world's largest emitter, has pledged to peak carbon emissions before 2030 and achieve carbon neutrality by 2060 (Xu et al., 2024). India, while prioritizing economic development, has committed to increasing its non-fossil fuel-based installed electricity capacity to 500 GW by 2030

(Dasgupta and Sarangi, 2021). These targets, while varying in ambition and timelines, demonstrate a growing global commitment to addressing climate change.

Using renewable energy, particularly solar energy, is a key option for reducing greenhouse gas emissions. Developed countries are leading the charge in solar energy adoption, with ambitious targets aimed at decarbonizing their economies. The European Union, for example, has set a goal of achieving at least 40% of its gross final energy consumption from renewable sources by 2030 (Di Foggia and Beccarello, 2024), with solar playing a significant role. The United States, driven by policies like the Inflation Reduction Act, is witnessing a surge in solar installations, aiming for significant decarbonization across sectors (Knox-Hayes et al., 2023). Germany, a pioneer in renewable energy, continues to expand its solar capacity, driven by ambitious targets and a strong policy framework (Gómez-Calvet and Gómez-Calvet, 2025). Japan, with limited fossil fuel resources, is heavily investing in solar energy to enhance energy security and meet its climate commitments (Li et al., 2019). These ambitious targets demonstrate the growing commitment of developed countries to harnessing solar power to achieve a sustainable energy future.

While, developing countries are also increasingly prioritizing solar energy in their energy transition plans, aiming to mitigate climate change, enhance energy security, and foster economic growth. India, for instance, has set an ambitious target of 450 GW of installed solar capacity by 2030 (Singh et al., 2023). China, a global leader in solar manufacturing, continues to expand its domestic solar capacity with dynamic targets adjusted based on economic and environmental factors. Brazil, with abundant solar resources, aims for 10 GW of solar power by 2030 as part of its energy diversification strategy (Chadly et al., 2024). South Africa, recognizing solar's potential to address energy poverty, has established ambitious renewable energy targets with a significant solar component (Béres et al., 2024). Kenya, while a leader in geothermal energy, is also exploring solar power to expand energy access in rural areas (Rotich et al., 2024). These targets demonstrate the growing recognition of solar energy's potential to contribute to sustainable development in developing countries. Malaysia has set ambitious targets for solar PV energy as part of its renewable energy transition. The National Energy Transition Roadmap (NETR) aims to increase the share of renewable energy in the country's energy mix from 40% by 2040 to 70% by 2050, (Fernandez et al., 2024) with a significant portion coming from solar PV installations. This includes large-scale solar parks and rooftop solar installations on residential and commercial buildings. The government is actively promoting solar PV adoption through various initiatives and policies

Indonesia, as a developing country with a rapidly growing economy and population, faces significant challenges in balancing energy demand with environmental sustainability. The country's energy sector is heavily reliant on fossil fuels, which contribute significantly to greenhouse gas (GHG) emissions and exacerbate climate change. Recognizing the urgency of mitigating these emissions, the Indonesian government has committed to achieving ambitious climate goals, including net-zero emissions by 2060 (Kumaraswamy et al., 2024; Siregar, 2024). This commitment is embodied in the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050), a roadmap designed to guide Indonesia toward a sustainable, low-carbon future (Government of Indonesia, 2021; UNFCCC.INT, 2024).

Renewable energy, particularly solar photovoltaic (PV) systems, is a key component of Indonesia's strategy to transition from a fossil fuel-dominated energy mix to one that leverages the country's abundant renewable energy resources. Solar energy holds significant promise due to Indonesia's geographical location, which provides high solar irradiance across most of its regions. Despite this potential, the current adoption rate of solar PV systems remains relatively low, hindered by regulatory, financial, and technical barriers (Tarigan, 2020; 2023). Moreover, while the role of renewable energy in general has been acknowledged in national strategies, the specific contribution of solar PV energy to GHG emission reductions needs further exploration to better understand its potential and to inform policy decisions.

The primary objective of this paper is to evaluate the role of solar photovoltaic (PV) energy in reducing greenhouse gas (GHG) emissions within the framework of Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050). To achieve this, the study aims to map the targets for solar PV energy deployment as outlined in the LTS-LCCR 2050 and assess the progress made toward achieving these targets. Additionally, it seeks to analyze historical and projected trends in solar PV system installations across Indonesia, identifying key drivers and barriers that influence adoption. The research also evaluates the effectiveness of existing government policies and regulatory frameworks in promoting solar PV energy deployment, highlighting areas where improvements or additional initiatives are necessary. Furthermore, this paper explores the potential of solar energy resources in Indonesia by focusing on geographical and technical feasibility for large-scale solar PV adoption. A crucial component of this study is the calculation of solar PV energy's contribution to GHG emission reduction targets, quantifying the avoided emissions from its deployment. Finally, the paper aims to provide actionable recommendations for policymakers and stakeholders to enhance the role of solar PV energy in achieving Indonesia's climate resilience and low-carbon development objectives. Through these efforts, the research aspires to contribute to the advancement of renewable energy strategies in Indonesia and support the country's transition toward a sustainable energy future

2. METHODOLOGY

This study employs a systematic and comprehensive approach to analyze the role of solar photovoltaic (PV) energy in achieving Indonesia's greenhouse gas (GHG) emission reduction targets as outlined in the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050). The methodology is structured into several key components, each addressing critical aspects of solar PV deployment and its impact on climate resilience.

1. Mapping Solar PV Targets in LTS-LCCR 2050: The research begins by collecting and analyzing data on solar PV capacity targets as specified in the LTS-LCCR 2050. This includes

reviewing government policies, strategic plans, and official reports to identify the specific milestones and objectives set for solar PV deployment in Indonesia. This step provides a foundation for understanding the scale and scope of the targets.

2. Mapping Trends in Solar PV Installation: The study examines historical and current trends in solar PV installation across Indonesia. This involves analyzing data on annual installation rates, sectoral contributions (residential, commercial, industrial, and utility-scale), and geographical distribution. The trends are evaluated in the context of the LTS-LCCR 2050 targets to assess progress and identify areas requiring further action.
3. Mapping Solar Energy Potential: Indonesia's solar energy potential is mapped using solar irradiance data, regional characteristics, and technical feasibility studies. This step identifies areas with the highest solar energy potential and examines factors such as land availability, grid connectivity, and socio-economic conditions that influence the viability of large-scale solar PV deployment.
4. Calculating Solar PV's Contribution to GHG Emission Reductions: The study quantifies the potential contribution of solar PV systems to GHG emission reduction targets by comparing the emissions from solar PV generation with those from conventional fossil fuel-based electricity generation. The calculation considers solar PV performance data, grid emission factors, and the projected capacity of installed systems by 2050.
5. Analyzing Solar Energy Targets and Discussing Scenarios for Achievement: A detailed analysis of the solar energy targets is conducted, followed by the development and discussion of various scenarios to achieve the 113 GW solar PV capacity target by 2050. These scenarios consider factors such as growth rates, early and late-stage development, and potential policy interventions.
6. Analyzing GHG Emission Reductions from Solar PV Systems: The study evaluates the total GHG emission reductions achievable through the adoption of solar PV systems. This includes calculating the avoided emissions from transitioning away from coal and other fossil fuels to renewable solar energy and assessing the impact on Indonesia's overall climate goals.
7. Identifying Challenges in Achieving the Targets: Finally, the research identifies the key challenges to achieving the solar PV targets, including financial, technical, regulatory, and social barriers. This step involves reviewing policy frameworks, infrastructure readiness, and market conditions to highlight obstacles and propose actionable solutions for overcoming them.

This multi-faceted methodology ensures a holistic understanding of solar PV's role in Indonesia's low-carbon strategy and provides insights into the pathways, benefits, and challenges of achieving the ambitious targets set forth in the LTS-LCCR 2050.

3. RESULTS AND DISCUSSION

The Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050) serves as Indonesia's blueprint for achieving a sustainable, low-carbon, and climate-resilient future. It outlines strategies for reducing greenhouse gas emissions, adapting to the inevitable impacts of climate change, and promoting sustainable development. The strategy addresses mitigation through sectoral pathways, including transitioning to renewable energy, enhancing energy efficiency, and implementing sustainable land use practices. Simultaneously, it focuses on adaptation by proposing measures to build resilience in vulnerable sectors like water resources, agriculture, and coastal areas. Enabling factors such as institutional strengthening, technological innovation, financial mobilization, and public awareness are also emphasized to support the strategy's goals.

The LTS-LCCR 2050 sets ambitious targets to significantly reduce greenhouse gas emissions by 2050, aligning with global efforts to limit temperature rise to well below 2 degrees Celsius. Additionally, it prioritizes enhancing climate resilience for communities and ecosystems, aiming to reduce vulnerability while ensuring long-term sustainable development. These efforts are closely tied to Indonesia's broader sustainable development objectives, highlighting the interdependence between climate action and economic, social, and environmental progress.

3.1. Energy Sector of Indonesia's LTS-LCCR 2050

The energy sector is the second-largest contributor to greenhouse gas (GHG) emissions after Agriculture, Forestry, and Other Land Use (AFOLU). Key GHG-emitting activities within this sector include power generation, transportation (both passenger and freight), and energy consumption in industries, residential buildings, and commercial establishments. The level of GHG emissions is influenced by the scale and type of energy sources utilized, which are in turn shaped by the implementation of mitigation measures. Strategies to reduce emissions in the energy sector include: (i) Enhancing energy efficiency across all sub-sectors; (ii) replacing fossil fuels with renewable energy in power generation and transportation; and (iii) increasing electrification in buildings and transportation, provided that the electricity supply is simultaneously decarbonized.

Electricity demand in Indonesia primarily originates from residential, commercial, and industrial sectors, with a small portion currently attributed to transportation (e.g., trains). However, this dynamic is expected to shift significantly as transportation increasingly adopts electric vehicles (EVs). Over the past decade, Indonesia's electricity consumption has grown steadily, averaging an annual growth rate of 5.9%, rising from 135 TWh in 2009 to 240 TWh in 2019 (ESDM.GO.ID, 2020)

By 2023, household electrification in Indonesia had reached 99.7% (ESDM.GO.ID, 2023), with households connected to both on-grid systems powered by large power plants and off-grid systems, predominantly driven by renewable energy sources. Moving forward, the goal is to ensure universal electricity access for all households, leveraging a combination of grid connections, non-grid solutions, and rooftop solar photovoltaic (PV) installations.

Historical trends suggest electricity demand in Indonesia will continue to grow at approximately 5% annually. Consequently, investments in new generation capacity, replacements of existing infrastructure, and transmission network expansion will be necessary to keep pace. Currently, Indonesia's power generation relies predominantly on coal, supplemented by gas, hydropower, and geothermal sources. However, by 2050, the power sector is projected to be nearly decarbonized through a three-pronged approach: (1) Large-scale deployment of renewable energy sources, including hydro, geothermal, solar, wind, and biomass; (2) widespread adoption of carbon capture and storage/utilization (CCS/CCUS) technology in most coal-fired power plants; and (3) implementation of biomass-coal co-firing in power plants integrated with CCS (BECCS).

3.2. Renewable Energy Role for 2050

By 2050, Indonesia's power generation landscape is expected to undergo a transformative shift under the Low Carbon and Climate Resilience Pathway (LCCP). The projected energy mix will comprise 43% renewables, 38% coal, 10% natural gas, and 8% bioenergy with carbon capture and storage (BECCS). The renewable energy sources will include hydro, geothermal, solar PV, biomass, biofuel, and wind, highlighting the diverse nature of Indonesia's clean energy portfolio.

To achieve net-zero emissions from coal power plants, approximately 76% of these plants will be equipped with carbon capture and storage (CCS) technology. The installed capacities of renewable energy sources will be impressive, with solar PV leading at 113 GW, followed by hydro at 68 GW, geothermal at 23 GW, wind power at 17 GW, biomass at 13 GW, biofuel at 14 GW, and BECCS contributing 23 GW with negative emissions. However, the intermittent nature of some renewable sources, such as solar and wind, will necessitate the integration of these sources with stable baseload power supplies like coal power plants to ensure a reliable energy system.

The carbon intensity of power generation is projected to be significantly reduced to 104 grams of CO_2 per kWh, reflecting the sector's decarbonization efforts. Additionally, there will be an increased focus on developing off-grid and micro-grid solutions, particularly in remote areas. These systems will incorporate 100% renewable energy, requiring the deployment of smart micro-grids for efficient and reliable operation. Moreover, the anticipated widespread deployment of intermittent renewables will necessitate advanced smart grid systems capable of managing large-scale supply fluctuations and ensuring stability in the national grid. This integrated approach will be crucial for Indonesia to achieve its long-term low-carbon and climate-resilient energy goals.

3.3. Solar Photovoltaics Energy in Indonesia

The Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050) sets an ambitious target for solar PV systems to supply 113 GW of the national energy mix by 2050, accounting for approximately 42% of total power generation. This target aligns with Indonesia's abundant solar energy resources, which provide a strong foundation for scaling up PV system deployment.

As highlighted in the solar resource map in Figure 1 published by the World Bank Group and ESMAP (SolarGIS.com, 2024) most regions across Indonesia exhibit high solar irradiance levels, making them well-suited for solar energy utilization. The map shows average daily photovoltaic output (PVOUT) values ranging from 3.0 kWh/kWp to 4.6 kWh/kWp, translating to annual outputs of 1,095 to 1,680 kWh/kWp. Areas with the highest PV potential, such as Nusa Tenggara, Papua, Maluku, and southern parts of Sulawesi, East Java, and Bali, are ideal for large-scale PV development, while regions with moderate irradiance, like Sumatra and Kalimantan, are well-suited for decentralized systems, such as rooftop and off-grid solar PV.

This rich solar potential demonstrates the feasibility of achieving Indonesia's renewable energy goals. By leveraging these natural resources and strategically implementing PV systems, Indonesia can significantly contribute to its greenhouse gas emission reduction targets, enhance energy security, and expand electricity access to underserved communities, all of which are critical elements of the LTS-LCCR 2050 framework.

Despite Indonesia's abundant solar energy potential, the growth in PV system adoption has been relatively slow, as reflected in Figure 2 (pv-magazine.com, n.d.) chart illustrates the growth of Indonesia's installed solar power capacity from 2020 to the second quarter (Q2) of 2024, highlighting a steady upward trend in the deployment of solar photovoltaic (PV) systems. Total installed capacity increased from 170.66 MW in 2020 to 717.71 MW by Q2 2024, representing significant progress in scaling up solar power infrastructure.

The installed capacity comprises four main categories: Captive, off-grid, rooftop, and on-grid systems. On-grid systems contribute the largest share of capacity growth, reflecting the government's emphasis on integrating solar power into the national grid to meet rising electricity demand and support renewable energy targets. Rooftop solar installations have also seen a steady increase, driven by policies encouraging decentralized energy solutions for residential and commercial sectors. Off-grid and captive systems, while smaller in contribution, play a critical role in enhancing energy access in remote and underserved areas, particularly in regions where grid connectivity is limited.

This growth trajectory underscores the effectiveness of recent initiatives and policies aimed at promoting solar energy adoption in Indonesia. However, the capacity of 717.71 MW remains modest compared to the LTS-LCCR 2050 target of 113 GW for solar PV systems. Accelerating this growth will require further investment, policy support, and technological advancements to overcome existing challenges and fully harness Indonesia's abundant solar potential. This analysis highlights the need for sustained efforts to scale up solar PV deployment to meet national energy and climate goals.

3.4. Scenarios for Achieving 113 GW Solar PV by 2050

To calculate and create scenarios to achieve the 2050 target of 113 GW of installed solar PV capacity, we assume 1 GW of installed capacity by the end of 2024 as the baseline. We then calculate the required growth rates under different scenarios. Each scenario presents unique pathways to achieving the 113 GW target by

Figure 1: Photovoltaic power potential in Indonesia (SolarGIS.com, 2024)

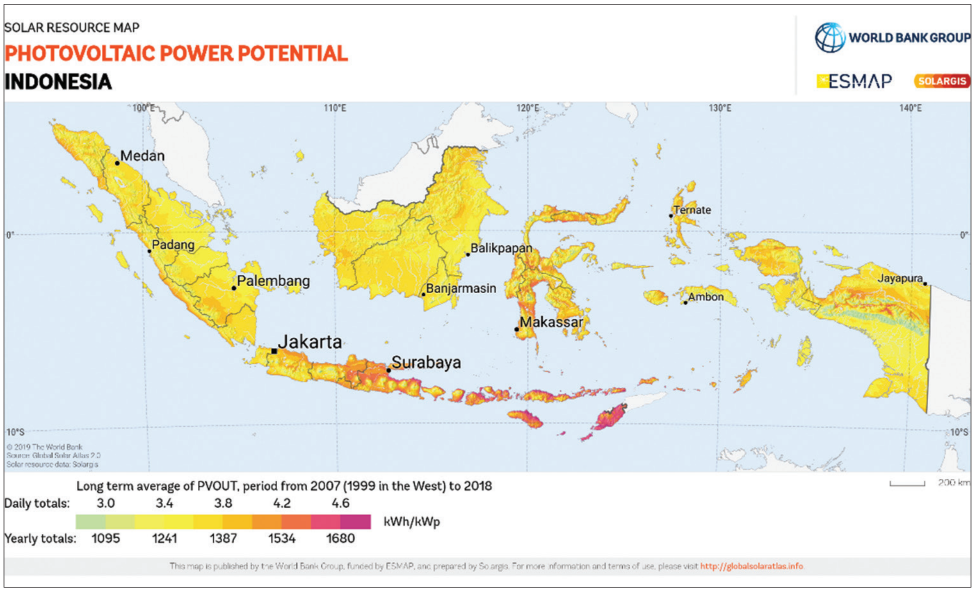
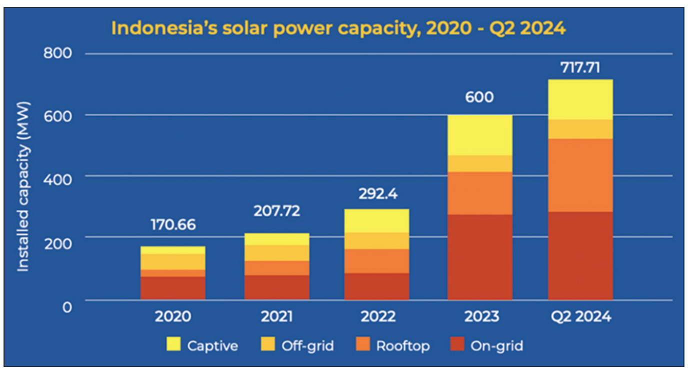


Figure 2: Indonesia's installed solar capacity (pv-magazine.com, n.d.)



2050. Scenario 1 offers a stable but challenging trajectory due to the need for sustained growth over 26 years. Scenario 2 allows a realistic, gradual buildup followed by rapid growth in later years, balancing initial barriers with future opportunities. Scenario 3 accelerates capacity development early on, setting a strong foundation but requiring significant initial investment and policy commitment. The choice of scenario will depend on Indonesia's financial resources, policy landscape, and readiness to overcome technical and institutional challenges.

3.4.1. Scenario 1 - Constant annual growth rate

The constant growth rate approach assumes consistent policy support, investment, and deployment of solar PV systems across the country. The capacity is projected to increase from 1 GW in 2024 to approximately 2.23 GW by 2030, 10.38 GW by 2040, and ultimately reach 113 GW by 2050.

This scenario requires stable financial and regulatory environments, as well as continuous technological advancements to maintain the growth rate over 26 years. While it is straightforward and predictable, achieving a consistent rate of growth over such a long period may present challenges due to market dynamics and external factors.

$$C_{2050} = C_{2024} \times (1 + r)^t \quad (1)$$

or

$$r = \left(\frac{C_{2050}}{C_{2024}}\right)^{\frac{1}{t}} - 1 \quad (2)$$

Where C_{2050} = Target capacity in 2050 = 113 GW; C_{2024} = Installed capacity in 2024 = 1 GW; r = Annual growth rate (in decimal form); and t = Number of years = 2050−2024 = 26 years. It can be calculated the installed capacity needs to grow at an average annual rate of 14.2% to reach 113 GW by 2050.

3.4.2. Scenario 2 - Based planning

This scenario assumes a slower initial growth rate of 8% per year for the first decade (2024–2034), followed by an accelerated growth rate of 20% per year from 2035 to 2050. Under this approach, the capacity would reach 2.16 GW by 2034 before increasing rapidly to meet the 113 GW target by 2050. The gradual ramp-up reflects the realistic challenges in the early years, such as overcoming regulatory barriers, securing investments, and addressing infrastructure limitations. The accelerated growth in later years capitalizes on reduced technology costs, increased public awareness, and strengthened policy frameworks. This scenario is practical, as it allows time to build the necessary foundation while ensuring exponential growth in later stages.

3.4.3. Scenario 3: Aggressive early deployment

This scenario focuses on rapid capacity growth during the first decade (2024–2034) with an annual growth rate of 20%, followed by a more moderate growth rate of 10% from 2035 to 2050. The capacity is projected to reach 6.19 GW by 2034, setting a strong foundation for the slower yet steady growth in the following years, ultimately achieving the 113 GW target by 2050. This approach emphasizes aggressive early investments, leveraging declining technology costs and policy momentum to accelerate deployment in the short term. It allows Indonesia to build momentum early, addressing energy security and emission reduction goals sooner while reducing the pressure for rapid expansion in later years. However, this scenario demands substantial upfront resources, making it challenging without robust financial and institutional support.

3.5. GHG Reduction Analysis

Figure 3 (instytutpe.pl, 2019) illustrates the greenhouse gas (GHG) emissions intensity of various energy sources, measured in tons of CO_2 per GWh (tCO_2/GWh) of electricity generated. It highlights the significant disparity in emissions between fossil fuels and renewable energy sources, underscoring the environmental benefits of transitioning to cleaner energy systems.

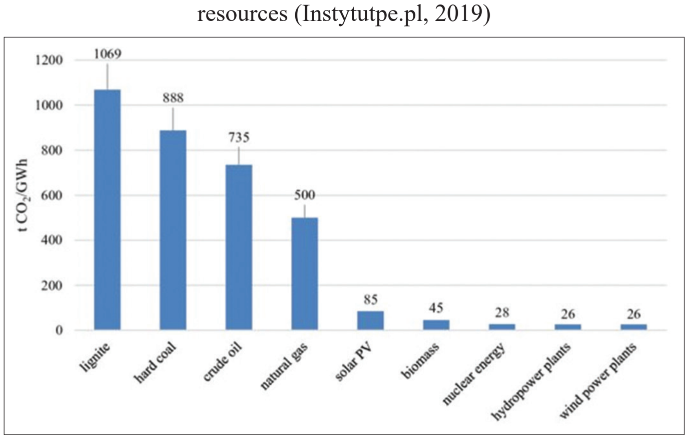
Lignite and hard coal exhibit the highest emissions intensities, at 1,069 tCO_2/GWh and 888 tCO_2/GWh, respectively, followed by crude oil (735 tCO_2/GWh) and natural gas (500 tCO_2/GWh). These fossil fuel-based energy sources are the primary contributors to GHG emissions in the power sector and emphasize the need for mitigation strategies, including the substitution of these fuels with cleaner alternatives.

In contrast, renewable energy sources demonstrate dramatically lower emissions. Solar PV and biomass produce 85 tCO_2/GWh and 45 tCO_2/GWh, respectively, due to their near-zero operational emissions but some emissions from their life cycle (e.g., manufacturing and transportation). Hydropower and wind power have the lowest emissions intensities, at 28 tCO_2/GWh and 26 tCO_2/GWh, respectively, making them among the most environmentally friendly options for power generation.

The analysis of greenhouse gas (GHG) reduction scenarios for achieving 113 GW of installed solar photovoltaic (PV) capacity by 2050 highlights the following results:

1. Total Emissions Reduction: The replacement of coal-based electricity generation with solar PV systems is estimated to reduce GHG emissions by approximately 794.87 million tons of CO_2 annually by 2050. This significant reduction underscores the critical role of transitioning to solar PV in meeting Indonesia's climate goals and decarbonizing the energy sector.
2. Constant Annual Growth Scenario: To achieve the target, the solar PV capacity must grow at an average annual rate of approximately 14.2% from 2024 to 2050. This scenario assumes steady and consistent investment, policy support, and deployment of solar PV systems throughout the 26-year period.
3. Gradual Ramp-Up Growth Scenario: In this scenario, the solar PV capacity grows at a slower rate of 8% annually during the first decade (2024–2034), reaching 2.16 GW by 2034. Subsequently, the growth accelerates to approximately 28.1% annually from 2035 to 2050 to achieve the target. This scenario reflects realistic initial challenges and anticipates stronger growth driven by improved policies, technological advancements, and declining costs in the later years.
4. Aggressive Early Deployment Scenario: This scenario focuses on rapid capacity expansion in the first decade (2024–2034), with an annual growth rate of 20%, resulting in an installed capacity of 6.19 GW by 2034. After this, the growth rate slows to approximately 10% annually from 2035 to 2050 to reach the target. This scenario emphasizes early momentum, leveraging technological innovations and initial policy support to establish a solid foundation for subsequent years.

Figure 3: Comparison of GHG Emissions for different energy resources (Instytutpe.pl, 2019)



Each scenario presents unique pathways for achieving Indonesia's solar PV deployment goals. While the constant growth scenario offers stability, the gradual ramp-up scenario balances initial challenges with accelerated progress in later years. The aggressive early deployment scenario, on the other hand, capitalizes on early investments to ensure rapid scaling of capacity. Regardless of the chosen pathway, achieving the 113 GW target will require strong policy frameworks, financial investments, and technological innovations. The results emphasize the importance of long-term planning and stakeholder collaboration in driving Indonesia's transition toward a low-carbon energy future

3.6. Challenges in Achieving Solar PV Deployment Scenarios

Achieving the ambitious target of 113 GW of installed solar PV capacity by 2050 presents several challenges, which vary across the three proposed scenarios. These challenges include financial, technical, regulatory, and social dimensions that must be addressed for successful implementation.

3.6.1. Financial and investment challenges

- High Initial Capital Costs: Solar PV installations, particularly large-scale deployments, require substantial upfront investments. While costs of solar PV technologies have been decreasing globally, financing remains a challenge in Indonesia, especially for off-grid and rural areas.
- Attracting Private Investments: Ensuring a stable policy framework to encourage private sector participation is critical. Inconsistent policies or delays in incentive programs could discourage investors.
- Infrastructure Development: Significant investments are needed for grid infrastructure upgrades, including the development of smart grids and energy storage systems, to accommodate the growing share of intermittent renewable energy

3.6.2. Technical challenges

- Intermittency of Solar Energy: The variability of solar power, especially in regions with inconsistent sunlight, poses a

challenge for reliable energy supply. Integration with stable baseload sources, such as coal or BECCS with carbon capture, and advancements in energy storage technologies are essential.
- Grid Integration: As solar PV capacity grows, ensuring grid stability and reliability becomes increasingly complex. The deployment of smart grids capable of handling fluctuations in supply and demand is critical for achieving the scenarios, particularly in areas with weak grid infrastructure.
- Maintenance and Operation: Scaling up solar PV installations requires a trained workforce for operation, maintenance, and monitoring, which might be lacking in certain regions.

3.6.3. Policy and regulatory challenges
- Policy Uncertainty: Long-term policies supporting renewable energy development, such as feed-in tariffs, subsidies, and tax incentives, must be consistent and predictable to maintain investor confidence.
- Bureaucratic Barriers: Complex approval processes and regulatory bottlenecks could delay project development and implementation.
- Land Use Conflicts: Identifying suitable locations for large-scale solar PV installations can be challenging, especially in densely populated areas or regions with competing land uses.

3.6.4. Social and awareness challenges
- Public Awareness and Acceptance: Limited understanding of the benefits of solar PV systems may hinder widespread adoption, especially for rooftop systems in residential and commercial sectors.
- Community Engagement: Involving local communities in planning and implementation is vital to ensure acceptance and address concerns related to land use and social impacts.
- Equity and Accessibility: Ensuring equitable access to solar energy, particularly for underserved and remote communities, requires targeted programs and subsidies.

4. CONCLUSION

This study highlights the critical role of solar photovoltaic (PV) energy in advancing Indonesia's long-term strategy for low carbon and climate resilience by 2050 (LTS-LCCR 2050). With an ambitious target of achieving 113 GW of installed solar PV capacity by 2050, solar energy is poised to be a cornerstone in Indonesia's efforts to transition toward a sustainable, low-carbon energy future. The findings reveal that achieving this target requires addressing multiple dimensions, including scaling up solar PV capacity, mitigating greenhouse gas (GHG) emissions, and overcoming technical, financial, and regulatory challenges. The analysis underscores Indonesia's immense solar energy potential, with high solar irradiance across most regions providing a strong foundation for solar PV development. However, the current pace of solar PV deployment remains slow, reflecting the need for enhanced policy support, targeted investments, and technological advancements. The transition to renewable energy, particularly solar PV, has the potential to significantly reduce GHG emissions, with an estimated reduction of approximately 794.87 million tons of CO_2 annually if solar PV systems replace coal-based electricity generation.

Three scenarios for achieving the 2050 target were explored: (1) Constant growth, (2) gradual ramp-up growth, and (3) aggressive early deployment. Each scenario presents unique pathways and challenges, with the constant growth scenario requiring sustained effort over the entire period, the gradual ramp-up scenario balancing initial barriers with accelerated growth, and the aggressive early deployment scenario leveraging early investments for rapid capacity expansion. Regardless of the pathway, achieving the target demands coordinated efforts across stakeholders, including the government, private sector, and local communities. The study also identifies key challenges, such as financial constraints, technical barriers related to grid integration and intermittency, regulatory bottlenecks, and social acceptance. Addressing these challenges will require strategic interventions, including the development of smart grids, energy storage solutions, financial incentives, and public awareness campaigns to accelerate solar PV adoption.

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