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Advancing Energy Transition: Solar PV and Battery Energy Storage Integration in Indonesia–South Korea Cooperation

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Abstract:
Purpose:
This study aims to analyze Indonesia's energy transition by modeling the integration of solar PV and Battery Energy Storage Systems (BESS) while assessing the role of Indonesia–South Korea cooperation in enhancing technological adoption, investment, and energy diplomacy.
Methodology:
This research employs a multidisciplinary approach combining quantitative mathematical modeling of solar PV–BESS integration with qualitative analysis of Indonesia–South Korea cooperation through international political economy and energy diplomacy frameworks.
Findings:
The study finds that integrating solar PV with Battery Energy Storage Systems (BESS) could significantly enhance Indonesia's grid reliability. Mathematical modeling shows that PV–BESS integration improves grid reliability and reduces coal reliance. reduce coal dependency, while Indonesia–South Korea cooperation provides technological, financial, and diplomatic leverage to accelerate the renewable energy transition.
Implication:
The findings imply that Indonesia should expand rooftop and utility-scale solar PV with BESS to secure the electricity supply, while hybrid systems can cut fuel costs in remote areas. Collaboration with South Korea can further accelerate deployment through technology transfer and local battery production.

INTRODUCTION

Indonesia's path toward a sustainable energy future remains overshadowed by persistent reliance on fossil fuels. In 2023, coal accounted for approximately 61.8 % of electricity generation, with renewables contributing just 19 % of the energy mix—solar and wind combined generating only 0.2 % (Ember, 2024). Despite the national ambition under the Rencana Umum Energi Nasional (RUEN, 2023) to achieve a 23 % renewable energy share by 2025, actual progress remains sluggish, at only 13.1 % in 2023 (ANTARA, 2024). In fact, the implementation of solar energy utilization can be described as follows:

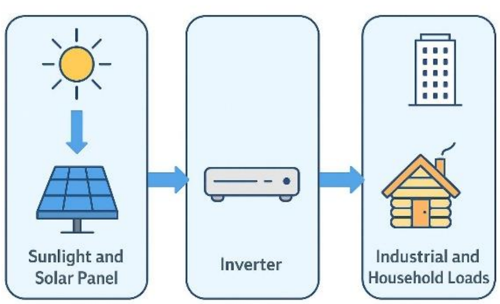

Figure 1. Implementation of Solar Energy Utilization

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The image above shows how sunlight is captured by solar panels and then converted by an inverter into alternating current that can be used for industrial and household loads. However, the actual utilization of this simple scheme in Indonesia is still very low compared to the existing technical potential.

In 2023, Indonesia's electricity consumption reached approximately 288.4 TWh, rising from 273.8 TWh in the previous year. Total electricity generation, including Independent Power Producers (IPP), is projected to reach 343.9 TWh in 2024. The power generation sector remains dominated by fossil fuels, with coal contributing around 66% of the energy mix. Consequently, energy-related CO_2 emissions were estimated at nearly 650 million tons in 2022. (Indra, 2025)

This discrepancy is particularly striking when contrasted with Indonesia's vast solar potential. The Ministry of Energy and Mineral Resources estimates solar potential at approximately 3,286 GW, and the Institute for Essential Services Reform (IESR,2023) even suggests it may reach 7,715 GW (Business-Indonesia,2024). However, by 2023, only 0.573 GW had been installed, equating to a mere 0.02 % of that potential (ANTARA,2024).

As of mid-2023, Indonesia's installed solar PV capacity stood at only 322.6 MW. Government projections suggest that by the end of the year, capacity could reach 700–800 MW, including rooftop PV installations, with an estimated investment of USD 700 million. Within the National Electricity Supply Business Plan (RUKN 2025–2060), the government targets 108.7 GW of solar capacity, projected to contribute 24.6% of the electricity mix by 2060. However, actual utilization remains critically low, at approximately 0.3 GW, which is less than 1% of the nation's technical potential.

To overcome the challenge of intermittency inherent to solar PV, Battery Energy Storage Systems (BESS,2024) offer a promising solution. Technological advancements have significantly lowered costs—lithium-ion battery prices have dropped approximately 89 % since 2010 (e.g., IRENA). When combined with solar PV, BESS can enhance grid stability, enabling daytime generation to be stored and utilized during non-generation hours.

a) **Solar PV Output**

$$P_{PV}(t) = \eta \cdot A \cdot G(t)$$

Where:

- η = panel efficiency (~15–20%)
- A = installation area (m²)
- $G(t)$ = solar irradiation (W/m²)

b) **Variability and Intermittency**
Due to intermittency (nighttime, cloudy conditions), solar energy output is inherently unstable without backup storage.

c) **Energy Stored in BESS**

$$E_{BESS} = \int (P_{PV}(t) - P_{load}(t))\, dt$$

This represents the net energy available for storage after subtracting load demand.

Figure 2. Solar PV, BESS Can Enhance Grid Stability

In this context, cooperation between Indonesia and South Korea takes on strategic importance. South Korea leads globally in battery and energy storage innovation, driven by corporations like LG Energy Solution and Samsung SDI. Joint investments like the recent establishment of Indonesia's first battery cell factory by Hyundai and LG Energy Solution, valued at USD 1.1 billion, highlight growing industrial synergy and transfer of expertise

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in energy storage solutions (Financial Times,2024). Assume Indonesia deploys 10 GWp of solar capacity from its current potential. If operating at an equivalent of 1,200 full-load hours per year, then:

$$P\ Annual = 10 \text{ X } 1{,}200 = 12{,}000 \text{ GWh} = 12\text{TWh}$$

With a BESS capacity sufficient to store 25% of daily generation, fluctuations could be significantly mitigated—thereby enhancing grid reliability and reducing coal dependency. Indonesia–South Korea cooperation could accelerate the deployment of high-efficiency solar PV and advanced BESS technologies. It could be realized through joint investment, R&D collaboration, and policy support, such as revising the local content requirement for solar PV (from 40% to 20%). Furthermore, international financing frameworks—such as the Just Energy Transition Partnership (JETP, 2023), valued at USD 22 billion—can be leveraged to expand field implementation. Indonesia's rising electricity demand, combined with the dominance of coal and the underutilization of solar PV, represents a critical bottleneck in the energy transition. Simple mathematical modeling demonstrates that utilizing only a fraction of the solar potential, supported by BESS, could make a significant contribution to the national energy mix. Technological cooperation with South Korea offers a strategic pathway to bridging gaps in capacity, efficiency, and investment, while simultaneously reinforcing energy diplomacy.

Based on this case, the Researcher Focused research on problem formulation is To what extent do fossil fuel dominance and the underutilization of solar PV hinder Indonesia's energy transition? How can the mathematical integration of solar PV with Battery Energy Storage Systems (BESS) improve the reliability of Indonesia's power system? What role can Indonesia–South Korea technological cooperation play in realizing such integration?

The conceptual framework of this study integrates three disciplinary perspectives—energy systems (physics), applied mathematics, and international relations—to address Indonesia's energy transition challenges.

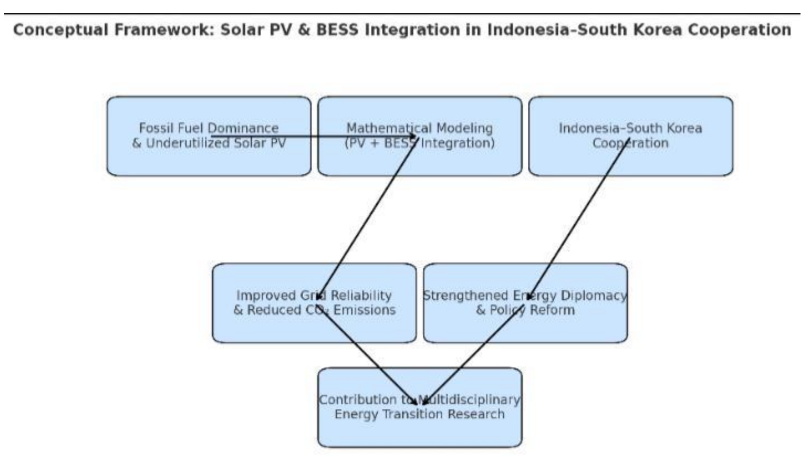

Figure 3. Conceptual Framework

A the problem level, Indonesia's electricity sector remains dominated by fossil fuels, while the utilization of solar photovoltaic (PV) is severely underdeveloped relative to its vast technical potential. This structural imbalance creates two interrelated challenges: high dependence on coal and the intermittency of renewable energy generation. A the analytical level, the study applies a mathematical modeling approach to quantify the contribution of solar PV when combined with Battery Energy Storage Systems (BESS). Through scenario analysis of different installed capacities and storage proportions, the model projects improvements in grid reliability, reductions in coal dependency, and potential CO_2 emission reductions.

Parallel to this, the study incorporates a policy and cooperation dimension, focusing on Indonesia–South Korea collaboration. South Korea's leadership in battery technology and its ongoing industrial investments in Indonesia provide a practical foundation for joint innovation, technology transfer, and financing. This cooperation is analyzed within the framework of energy diplomacy and international political economy (IPE), emphasizing how bilateral engagement can strengthen policy reform, industrial capacity, and transnational energy governance.

At the outcome level, the framework demonstrates that the integration of solar PV and BESS can yield two synergistic benefits:

1. Technical outcomes in the form of enhanced grid reliability and reduced greenhouse gas emissions.
2. Institutional outcomes through reinforced energy diplomacy, improved policy frameworks, and deeper bilateral cooperation.

Ultimately, the framework positions this research as a multidisciplinary contribution that bridges the gap between technological feasibility, mathematical quantification, and international cooperation. By synthesizing these dimensions, the study not only highlights the technical potential of PV–BESS integration but also underscores its strategic role in advancing Indonesia's sustainable energy transition.

Finally, this bilateral collaboration aligns with both countries' net-zero ambitions: Indonesia aims for carbon neutrality by 2050, while South Korea targets 2050–2060. Through technology transfer, capacity-building, and strategic policy frameworks, their partnership can significantly amplify Indonesia's renewable energy deployment and reliability, exemplifying how "Advancing Energy Transition: Solar PV and Battery Energy Storage Integration in Indonesia–South Korea Cooperation" not only integrates clean technologies, energies and applied mathematics, but also strengthens formal and informal energy diplomacy. Based on this problem formulation, researchers are expected to be able to formulate it into a completed study.

METHODS

This study focuses on examining the potential of Indonesia's energy transition through the integration of solar photovoltaic (PV) and battery energy storage systems (BESS), while also considering the role of international cooperation—particularly with South Korea—in supporting this transition. The research adopts a multidisciplinary approach that combines applied mathematics, energy systems modeling, and international relations analysis (Ozawa & Pollitt, 2019; Şatana, 2024).

The study uses a quantitative modeling approach to estimate the potential electricity generation from solar PV under specific assumptions. Based on Indonesia's current renewable energy outlook (ESDM, 2021; PLN, 2022), a scenario of deploying 10 GWp of solar capacity is considered. For this capacity, we assume an equivalent of 1,200 full-load hours per year, which results in an annual generation potential of approximately 12 TWh (IEA, 2021; IRENA, 2022). To address the issue of intermittency, the study further assumes that a BESS capacity equal to 25% of daily generation is installed, enabling the storage of surplus energy and stabilization of grid reliability (IRENA, 2020). The mathematical formulations applied in this study are consistent with standard solar PV output modeling, where output is defined as a function of panel efficiency, installation area, and solar irradiation (Sugiyono, 2020; Masters, 2013). Net stored energy is estimated by subtracting load demand from solar output.

Data for solar irradiation, generation potential, and renewable integration scenarios were collected from publicly available reports of the Ministry of Energy and Mineral Resources (ESDM,2021), PLN, as well as international organizations such as the International Energy Agency (IEA,2022) and IRENA. Additional supporting data were obtained from academic literature and industry reports related to energy transition and battery technology (Nayak et al., 2021).

In addition to quantitative modeling, the study employs qualitative analysis to examine the international cooperation dimension. Official documents and reports related to bilateral energy collaboration between Indonesia

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and South Korea were reviewed, including agreements on technology transfer, battery industry development, and renewable energy investment (MOEF, 2021; MOTIE Korea, 2021). These sources were analyzed through the lens of international political economy and energy diplomacy frameworks to assess how such cooperation could accelerate Indonesia's renewable energy transition. (Keohane & Nye, 2012; Şatana, 2024)

Data Analysis. Data analysis was conducted using two complementary approaches: quantitative technical analysis and qualitative policy analysis.

1. Quantitative Technical Analysis. Mathematical modeling was applied to estimate solar electricity (Drs Hidayat Sardi,2023), output using the formula:

$$P_{PV}(t) = \eta \cdot A \cdot G(t)$$

- Net storable energy was computed as:

$$E_{BESS} = \int (P_{PV}(t) - P_{load}(t))dt$$

- Scenario-based simulations were conducted to estimate annual generation potential and the contribution of BESS in mitigating supply fluctuations.

Figure 4. Mathematical modeling

2. Qualitative Policy and International Cooperation Analysis. Official documents, policy reports, and publications concerning Indonesia–South Korea energy cooperation were reviewed to assess energy diplomacy, technology transfer, and investment opportunities (Sugiyono, 2020).

- The analysis applied an International Political Economy (IPE) framework to map state interests, private sector involvement, and the geopolitical implications of Indonesia's energy transition.
- Findings were classified into four thematic categories: (1) renewable energy technology, (2) battery industry development, (3) investment mechanisms, and (4) energy diplomacy.

By combining technical modeling with international relations analysis, this study provides an integrated perspective on both the feasibility of large-scale PV–BESS deployment in Indonesia and the political-economic enablers of the transition.

RESULTS AND DISCUSSION

Indonesia's Energy Landscape and Solar PV Potential. Indonesia's electricity sector currently remains heavily dependent on fossil fuels, particularly coal, which accounted for approximately 66% of the total electricity mix by 2023 (Indra, 2025). This high dependence on coal not only impacts the national energy structure but also significantly impacts the environment. CO_2 emissions from the energy sector are estimated to reach nearly 650 million tons by 2022, making Indonesia a major contributor to greenhouse gas emissions in Southeast Asia. This situation indicates that although Indonesia has emissions reduction and energy transition targets, their implementation is still far from optimal. The Indonesian government, through its National Energy General Plan (RUEN, 2023), targets a renewable energy mix of 23% by 2025. However, the actual use of renewable energy by 2023 only reached 13.1% (ANTARA, 2024), indicating a significant gap between the target and achievement. This low achievement reflects various structural challenges, ranging from inadequate infrastructure capacity to limited investment and regulations supporting renewable energy development.

The theoretical foundation of this section is grounded in the physics of renewable energy, which provides the essential framework for understanding solar PV potential in Indonesia. Boyle (2012), in Renewable Energy: Power for a Sustainable Future, argues that renewable energy sources must be analyzed through their underlying

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physical principles, particularly solar radiation intensity, photovoltaic material efficiency, and geographic availability. Likewise, Twidell and Weir (2015) in Renewable Energy Resources emphasize that solar energy is inherently intermittent due to diurnal and seasonal variations, which require both technical assessment and system-level solutions to ensure stability. From a physics-based perspective, the availability of solar energy is a direct function of extraterrestrial radiation, atmospheric conditions, and surface orientation, which together define the upper bound of the potential energy output. These principles form the scientific rationale for highlighting the disparity between Indonesia's immense solar potential—estimated between 3,286 GW (MoEMR, 2023) and 7,715 GW (IESR, 2023)—and its actual installed capacity of only 0.573 GW in 2023.

Further elaboration of the physical modeling of solar energy is provided by Duffie and Beckman (2013) in Solar Engineering of Thermal Processes, a seminal text that formulates the equations to calculate solar availability, irradiation, and system conversion efficiency. Their approach provides the methodological underpinning for analyzing the conversion of solar irradiance into usable electricity while accounting for inverter losses, transmission inefficiencies, and climate variations. Applying these principles to Indonesia, it becomes evident that the physical barriers of intermittency and system losses significantly reduce the realizable portion of the theoretical potential. Therefore, Section 4.1 builds on these renewable energy physics frameworks to argue that Indonesia's limited deployment of PV reflects not only policy and infrastructural gaps but also the absence of a comprehensive application of physical modeling to optimize renewable energy integration.

From a physics and energy systems perspective, this situation indicates a significant technical gap. Although Indonesia has enormous solar energy potential, its utilization remains very limited. According to the Ministry of Energy and Mineral Resources (ESDM), Indonesia's solar energy potential reaches 3,286 GW, while the Institute for Essential Services Reform (IESR, 2023) estimates it could reach 7,715 GW. This abundant potential can support the national energy transition if optimally utilized through the integration of appropriate technologies and careful infrastructure planning. However, installed capacity as of 2023 was only 0.573 GW, or less than 0.02% of the existing technical potential (ANTARA, 2024). This low installed capacity is due to several factors, including the intermittency of solar energy, which varies daily and seasonally, the limited capacity of the electricity grid to accommodate fluctuating renewable energy, and economic and policy constraints that do not yet support the massive development of PV. As a result, the utilization of solar energy has not made a significant contribution to reducing dependence on coal and carbon emissions. In this context, integrating solar PV with Battery Energy Storage Systems (BESS) is a promising solution. With BESS, energy generated during the day can be stored and used when demand is high or solar intensity is low, thereby improving grid stability. This approach not only offers technical advantages from an energy system perspective but also opens up opportunities for reduced reliance on coal and lower CO_2 emissions, while accelerating the sustainable energy transition in Indonesia (IESR, 2023; Ember, 2024; ANTARA, 2024).

Some factors that cause low utilization of solar energy include:

Table 1. Solar PV Potential, Installed Capacity, and Projection BESS in Indonesia

Description	PV Potential	Installed Capacity	Installed Capacity	BESS Projection	CO^2 Emissions
Potential	3.286 GW	—	—	—	—
Capacity in 2023	573 MW	—	—	—	—
Capacity in 2024	700-800 MW	10% portion	10% portion	25%	0.1 Gt
Projection 2030	10 GW	20%	20%	20%	0.1 Gt
Projection 2040	15 GW	40%	40%	40%	0.3 Gt

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1. Intermittency of Solar Energy. The intermittency or variable nature of solar energy is one of the main obstacles to its utilization. The intensity of solar radiation is not always constant throughout the day; in the morning and afternoon, available energy is much lower than during the day. Furthermore, weather conditions such as cloudy or rainy weather can drastically reduce the potential energy that can be generated. Seasonal changes also affect the availability of solar energy; for example, during the rainy season or winter, the duration of sunlight is shorter, so the electrical output from photovoltaic (PV) systems tends to decrease. This variability makes energy supply planning more complex, especially when solar energy is integrated into a power grid that requires a stable supply. In addition to weather and seasonal factors, the intermittency of solar energy also requires energy storage systems or integration with other energy sources to maintain a stable power supply. Without supporting systems such as batteries or fossil-based backup energy, fluctuations in solar energy production can cause instability in the power grid, including the risk of blackouts or overload at certain points. In the context of intermittent renewable energy, energy management and production prediction are key to ensuring the system can operate reliably. It also requires sophisticated monitoring and control devices to balance production and consumption in real time. (IESR, 2023)

From an investment and development perspective, this intermittency is a concern for the government and investors. Uncertainty in energy production results in higher financial risks due to the uncertain potential return on investment (ROI). Therefore, mitigation strategies such as developing hybrid systems—combining solar energy with other, more stable sources of energy—or innovations in energy storage technology are a key focus for increasing sustainable solar energy utilization. Without these measures, Indonesia's abundant solar energy potential cannot be optimally utilized. (ESDM, 2024)

2. Limitations of Electricity Grid Infrastructure. The current electricity grid infrastructure is a major limiting factor in solar energy development. Electricity grids in many regions are still designed to support a stable supply of energy from conventional power plants, such as coal or gas. When variable solar energy is fed into the grid, the system often lacks the flexibility to adjust to power fluctuations, resulting in an imbalance between supply and demand. It becomes even more complex in remote areas or those with less robust electricity grids, where integrating renewable energy requires expensive and technically complex infrastructure upgrades. (PLN, 2024)

Furthermore, limited transmission and distribution systems make it difficult to distribute solar energy generated in certain locations to consumption centers. For example, large-scale solar panels installed in rural areas or areas with high solar radiation may not be able to deliver electricity to major cities if the transmission grid capacity is inadequate. This obstacle reduces the effectiveness of solar energy utilization nationally because, despite the abundant potential of renewable resources, energy distribution remains a critical issue. Modernizing the electricity grid, including smart grids and intelligent energy management systems, is a crucial step to address this challenge. (BESS,2023)

Another relevant factor is the integration of energy storage systems into the electricity grid. The availability of large-scale batteries or energy storage systems (ESS) allows solar energy generated during peak periods to be stored and used during times of high demand or low sunlight. However, implementing ESS requires high costs, thorough technical planning, and supportive policies to ensure synergy with the existing electricity grid. Without adequate infrastructure support, solar energy utilization will remain limited, despite its vast natural resource potential.

3. Economics and Policy Barriers. Economic barriers are a major barrier to solar energy adoption in Indonesia. The initial investment for installing photovoltaic systems, especially on a large scale, remains relatively high compared to the cost of electricity from fossil fuels. The price of PV modules, inverters, and energy storage systems contributes significantly to the total project cost. For households or medium-sized businesses, these costs are often a significant limiting factor. Furthermore, maintenance and replacement of damaged components add to the cost burden, making solar energy less attractive than cheaper conventional options (ESDM,2023)

Policy factors also contribute to the low adoption of solar energy. Unequal regulations and limited incentives discourage many investors from entering the sector. For example, feed-in tariffs or subsidies for renewable energy

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are still suboptimal in many regions. Furthermore, permitting for construction and grid interconnection often takes a long time and incurs additional costs. This regulatory uncertainty poses risks for solar energy developers, slowing the sector's growth nationally (ANTARANEWS,2022)

Overall, economic and policy barriers create a mutually reinforcing cycle: high costs discourage investment, while inadequate regulations slow the adoption of new technologies. To address this issue, the government needs to formulate clear and consistent policies, including fiscal incentives, streamlined licensing processes, and financial support programs for investors and the public. With the right strategy, these economic and policy barriers can be minimized, giving solar energy a greater opportunity to grow and contribute significantly to the national energy mix.

Mathematical Quantification of PV–BESS Integration. After understanding Indonesia's energy landscape and the vast potential of solar energy, as discussed in the previous subsection, the next step is to mathematically quantify the scenario of integrating solar PV with a Battery Energy Storage System (BESS). This mathematical approach is crucial because it bridges the gap between the enormous technical potential and the real need for data-driven energy planning. Through simple yet representative modeling, this study can estimate the contribution of PV capacity combined with a BESS to reducing dependence on coal, increasing electricity system reliability, and reducing carbon emissions. Therefore, this quantitative analysis is not merely a theoretical exercise but also provides a relevant scientific basis for policymakers and investors in designing Indonesia's energy transition strategy.

$$Ppv\ (t) = n\,.\,A\,.\,G(t)$$

The mathematical foundation of PV–BESS modeling is inherently rooted in calculus and functional analysis, branches of pure mathematics that provide the tools to formalize physical energy flows. The expression of solar PV output is essentially a functional relationship mapping time-dependent solar irradiance G(t) to instantaneous power generation. This formulation can be traced to the broader tradition of differential calculus, where changes in an independent variable (irradiance as a function of time) yield proportional changes in a dependent variable (energy output). Such a representation follows the mathematical principles articulated by Isaac Newton (1687) in Philosophiae Naturalis Principia Mathematica and further refined in modern applied contexts by Walter Rudin (1976) in Principles of Mathematical Analysis. By expressing PV output as a function of irradiance, the model relies on the assumption of continuity and differentiability, two central concepts in real analysis that enable the use of calculus to evaluate time-varying solar dynamics.

Building on this, the integration of energy storage in BESS is mathematically formalized through the integral equation.

$$Ebess = \int \ \big(Ppv(t) - Pload(t)\big), dt$$

This formulation derives directly from the fundamental theorem of calculus, which connects instantaneous rates of change (power generation minus demand) to cumulative quantities (stored energy). In this sense, energy storage is modeled as the integral of a residual function, representing the accumulation of net power over time. Such an approach is aligned with the work of Courant and Hilbert (1953) in Methods of Mathematical Physics, who demonstrated how integral equations provide rigorous frameworks for modeling dynamic systems. Furthermore, the inclusion of intermittency acknowledges that it is not a smooth function but is instead subject to discontinuities due to weather and diurnal variation. It requires the application of piecewise continuous functions and approximation methods within functional analysis, as emphasized by Luenberger (1979) in Introduction to Dynamic Systems. Therefore, the PV–BESS model is not merely an engineering heuristic but

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rather a direct application of core mathematical principles—differential calculus, integral calculus, and real analysis—to represent, quantify, and predict the behavior of renewable energy systems under variable conditions.

1.Solar PV Output in the Indonesian Context. Indonesia has an average Global Horizontal Irradiance (GHI) between 4.0–5.5 kWh/m²/day (BMKG, 2023).

$$Ppv\ (t) = n\ .\ A\ .\ G(t)$$

It corresponds to approximately 1,200–1,500 full-load hours (FLH) annually for grid-connected solar PV. The instantaneous power output can be expressed as:

n: PV System efficiency (15-20% at module level; 80-85% at system level after derating losses).
A: Installation area (m²)
G(t): Solar Irradiation at time ^{t}(W/m²).

Where:

$$Epv = P\ installed\ \text{x}\ H\ full - load\ \text{x}\ N\ system$$

$$Epv = 10\ GWp\ \text{x}\ 1{,}200h\ \text{x}\ 0{,}85 = 10{,}2\ TWh/year$$

For this study, we assume a 10 GWp installed PV capacity with a conservative FLH of 1,200 h/year and a system efficiency of 85%, yielding:

This figure is small compared to Indonesia's total electricity consumption (~300 TWh in 2023), but it represents a significant initial contribution given the low baseline of solar deployment.

2. Variability and the Role of BESS. Due to diurnal cycles and weather conditions, PV output is highly intermittent. Without storage, a large fraction of PV generation may not align with demand, particularly as Indonesia's peak load typically occurs between 18:00–22:00 WIB. (PLN,2024)

To address this, BESS can store excess midday PV output and discharge during evening peaks. The net storable energy is expressed as:

$$Ebess = f\ \big(Ppv(t) - Pload(t)\big)\ dt$$

With operational limits:

$$Ebess(t) < Cbess$$

Where C_{BESS} is the battery capacity

3.Scenario Simulation: 10 GWp PV with 25% BESS Storage. Assuming that 25% of daily PV generation is stored:

- Daily PV generation:

$$\frac{10.2\ TWh}{365} = 27{,}9\ \text{GWh/day}$$

- BESS Capacity (25%):

$$Cbess = 7.0\ GWh$$

If discharged over 4 hours during peak load, this corresponds to a BESS power rating of ~1.75 GW.

4. Impact Assessment.

- Coal Displacement. Indonesia's coal plants typically operate with an average emission factor of 0.85–0.95 tCO_2/MWh (PLN, 2023). If BESS enables shifting 7.0 GWh/day from PV into evening demand:

$$CO2 = 7{,}000 \frac{MWh}{day} x\ 365\ x \frac{0.9t}{MWh} = 2.3\ co2/year$$

- Grid Reliability. By smoothing fluctuations and shaving 1.75 GW of peak demand, PV–BESS can reduce pressure on peaker plants (gas turbines and coal cycling). It enhances grid stability and reduces fuel costs.
- Curtailment Reduction. Without BESS, excess midday PV may be curtailed. Storage ensures higher effective utilization of PV capacity, increasing the capacity factor of the integrated system.

5. Sensitivity and Policy Relevance.

- If FLH increases to 1,400 h/year (locations such as East Nusa Tenggara), the annual PV output rises to 11.9 TWh, raising CO_2 reductions by ~15%.
- If storage share increases to 40%, evening displacement rises proportionally, potentially shaving ~3 GW of peak load.
- If the round-trip efficiency of BESS is 90%, ~10% of stored energy is lost, highlighting the importance of high-efficiency lithium-ion or next-gen chemistries.

This quantitative modeling provides a data-driven foundation for policymakers. It demonstrates how scaling PV–BESS directly supports Indonesia's RUEN 23% renewables by 2025 and JETP (USD 22 billion) targets by quantifying tangible coal displacement and emissions reduction.

Policy and International Cooperation: Indonesia–South Korea Collaboration. The Phenomenon of Cooperation and Policy from the perspective of international relations and the political economy of energy, the Indonesia–South Korea partnership demonstrates a convergence of technology statecraft, industrial diplomacy, and transition financing. In terms of technology transfer and downstream industrialization, a milestone was the establishment of Indonesia's first electric vehicle (EV) battery cell factory operated by HLI Green Power, a joint venture between Hyundai Motor Group and LG Energy Solution, with an initial investment of approximately US$1.1 billion and a production capacity of 10 GWh per year. This project, initiated through a memorandum of understanding in 2021, officially commenced operations in 2024 in Karawang, West Java (Hyundai Motor Group, 2021; Reuters, 2024; Financial Times, 2024). The Indonesian government has also announced expansion plans with an additional US$1.7 billion investment to scale up production capacity and strengthen local supply chains, even as LG Energy Solution withdrew from a separate IDR 142 trillion EV supply chain project. Nonetheless, LG reaffirmed its commitment to the joint venture through HLI Green Power (Reuters, 2025). For Indonesia, this facility is not merely an inflow of foreign direct investment; it represents a strategic shift from exporting raw nickel to capturing greater value in high-technology manufacturing, thereby enhancing bargaining power in the regional supply chain and facilitating learning-by-doing for local human capital and suppliers (Financial Times, 2024).

On the financing architecture side, Indonesia signed the Just Energy Transition Partnership (JETP) at the G20 Bali Summit in 2022, securing US$20 billion in commitments from a coalition of international partners—half from public institutions and half from private investors. This framework was translated into the Comprehensive Investment and Policy Plan (CIPP) in 2023, which outlined investment pathways and policy reforms to accelerate power sector decarbonization, including renewable energy integration and Battery Energy Storage Systems (BESS)

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as enabling infrastructure (UNDP, 2022; JETP CIPP, 2023). Geopolitically, JETP provides Indonesia with a credible anchor for multi-stakeholder policy dialogue involving government agencies, development finance institutions, and private sector actors, while positioning the country within the broader G7-led global transition architecture. However, actual fund disbursement has been gradual, with bankable project pipelines and regulatory reforms remaining prerequisites for scaling up investment (Reuters, 2024; Columbia SIPA, 2025).

In terms of policy cooperation and ecosystem development, the Indonesian and South Korean governments signed a memorandum of understanding on the development of an EV ecosystem, covering both battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs). This agreement integrates upstream mineral resources, midstream precursor production, and downstream battery cell and vehicle manufacturing (ANTARA, 2023). These initiatives align with regional supply chain diversification strategies and broader clean energy cooperation, as reflected in subsequent investment pledges and technology partnerships (AP News, 2023). At the domestic power sector level, emerging procurement models now combine solar PV with BESS, such as the 50 MWp solar project in Indonesia's new capital (IKN) equipped with BESS, alongside other renewable PPAs incorporating storage elements—signaling a policy shift towards storage-enabled renewable deployment (PLN Nusantara Renewables, 2024; Chambers, 2024).

Substantively, the Indonesia–South Korea collaboration contributes three strategic values to PV–BESS deployment: (i) technology and process know-how transfer from leading global battery manufacturers (LG Energy Solution, Hyundai, Samsung SDI) through joint ventures, training, and local content development; (ii) industrial synergy connecting upstream nickel mining with midstream processing and downstream cell/pack manufacturing, thereby mitigating supply risks and cost volatility; and (iii) financing leverage through JETP and development finance that can reduce the cost of capital for utility-scale PV–BESS projects. Empirical data from the Institute for Essential Services Reform (IESR) confirms Indonesia's vast solar potential of more than 3.3 TWp, but utilization remains limited, underscoring the critical role of foreign investment and policy learning through international partnerships to bridge the "implementation gap" (IESR, 2023/2024).

Nevertheless, governance challenges remain in ensuring that cross-border cooperation accelerates PV–BESS adoption. These include regulatory certainty and project bankability (tariff structures, curtailment risks, and capacity payment schemes for BESS), alignment between local content requirements (TKDN) and economies of scale in manufacturing, transmission readiness to integrate variable solar PV, and the timely disbursement of blended finance under JETP. Recent developments—from battery cell production to renewable projects with embedded storage—indicate progressive policy direction. However, consistent implementation and effective de-risking mechanisms will determine whether Indonesia–South Korea cooperation evolves from symbolic cooperation into transformational cooperation, with measurable impacts on emission reduction, supply security, and technological sovereignty in Indonesia's power sector (Reuters, 2024–2025; JETP CIPP, 2023; Financial Times, 2024; ANTARA, 2023).

Theoretical Foundation of Liberalism in International Relations**.** Liberalism in international relations emphasizes the potential for cooperation, mutual gains, and institutional frameworks that mitigate conflict among states. Unlike realism, which views international politics as a zero-sum struggle for power, liberalism posits that states and non-state actors can achieve absolute gains through collaboration, economic interdependence, and the creation of regimes and institutions. Foundational contributions were made by scholars such as Robert Keohane and Joseph Nye, who developed the concept of complex interdependence, highlighting how economic ties and institutions reduce the likelihood of conflict while enhancing incentives for sustained cooperation (Keohane & Nye, 1977; Keohane, 1984). Liberalism assumes that states are not solely concerned with survival and relative power but are also motivated by economic prosperity, domestic preferences, and shared values. Thus, cooperation becomes not only possible but desirable, particularly when facilitated by regimes and international frameworks.

At its core, liberalism rests on three assumptions. First, states and non-state actors pursue absolute gains rather than competing only for relative advantages. Second, domestic preferences shape state behavior, suggesting

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that internal constituencies, including industries and civil society, play a role in foreign policy choices (Moravcsik, 1997). Third, international institutions reduce transaction costs, provide information, and enforce agreements, thereby enabling long-term cooperation (Keohane, 1984). In the context of energy transition, liberal institutionalism suggests that multilateral frameworks such as the Just Energy Transition Partnership (JETP) or bilateral agreements like the Indonesia–South Korea EV battery initiative serve as platforms for mutually beneficial cooperation, where both sides see convergence between domestic development goals and global climate commitments.

The Indonesia–South Korea partnership in solar PV and battery energy storage reflects liberal principles of absolute gains and interdependence. For Indonesia, the partnership enables technological upgrading, industrial diversification, and greater value capture in the global supply chain, shifting away from raw material dependency. For South Korea, cooperation ensures secure access to critical minerals such as nickel and cobalt while providing new markets for its advanced battery and EV industries (Reuters, 2024; Financial Times, 2024). Both sides benefit from the diffusion of technology and capital, creating a win–win dynamic rather than a zero-sum rivalry. This outcome directly resonates with liberal assumptions that economic interdependence incentivizes peaceful cooperation and creates mutual interests across borders (Keohane & Nye, 1977).

Moreover, liberalism highlights the role of institutions and norms in facilitating cooperation. The JETP framework, endorsed at the G20 Bali Summit, serves as an institutional anchor for financing and policy alignment, while the joint venture HLI Green Power illustrates how formal agreements reduce uncertainty and lock both parties into long-term collaboration. Through these institutional mechanisms, transaction costs are lowered, information asymmetry is reduced, and credible commitments are enforced, thereby sustaining cooperation. In practice, this has allowed Indonesia to attract billions in foreign investment while providing South Korea with stable supply chains. Viewed through the liberal lens, the Indonesia–South Korea PV–BESS cooperation exemplifies how interdependence, institutions, and mutual benefits transform energy diplomacy into a catalyst for sustainable development and climate action.

Integrated Multidisciplinary Insights: Indonesia–South Korea Cooperation in PV–BESS Development. The integration of solar photovoltaic (PV) and battery energy storage systems (BESS) in Indonesia is not only a matter of technological advancement but also a multidimensional process shaped by applied science, mathematical modeling, and international cooperation. From a physics perspective, PV–BESS integration represents a critical mechanism to stabilize variable solar generation, mitigate intermittency, and enhance grid resilience (Boyle, 2012). Mathematical models, as discussed in Section 4.2, quantify the potential electricity output and storage capacity, thereby providing data-driven insights for policymakers and investors (Kreyszig, 2011). However, these technical and quantitative insights cannot stand alone; they require international cooperation to mobilize capital, transfer knowledge, and build institutional capacity. In this regard, South Korea emerges as a strategic partner for Indonesia in accelerating its energy transition.

South Korea has established itself as a global leader in battery and storage technologies through firms such as LG Energy Solution, Samsung SDI, and Hyundai Motor Company (Lee, 2020). The bilateral cooperation between Indonesia and South Korea has already produced tangible outcomes, such as the construction of Indonesia's first integrated EV battery cell factory in Karawang, valued at USD 1.1 billion, a joint venture between Hyundai Motor Group and LG Energy Solution (Tempo, 2023). This industrial synergy is directly aligned with Indonesia's ambition to strengthen its domestic supply chain for renewable energy and storage, reducing dependency on imported technologies. At the same time, South Korea secures stable access to Indonesia's abundant nickel reserves, which are indispensable for lithium-ion battery production (IEA, 2022). It reflects the liberalist notion of mutual gains through interdependence, where both states benefit from collaboration based on complementary needs (Keohane & Nye, 1977).

Beyond industrial cooperation, the policy and financial dimensions are also critical. Indonesia's participation in the Just Energy Transition Partnership (JETP, 2023), which mobilizes USD 20 billion in climate finance, is

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complemented by bilateral arrangements with South Korea to expand renewable capacity and storage integration (World Bank, 2023). Such collaboration highlights the liberal institutionalist argument that international cooperation reduces transaction costs, facilitates technology transfer, and aligns national policies with global norms (Keohane, 1984). For Indonesia, this support alleviates domestic barriers such as limited grid infrastructure, financing challenges, and regulatory hurdles, while for South Korea, it expands market access for its green technology industries.

From a broader international relations perspective, the Indonesia–South Korea partnership illustrates how renewable energy transition can serve as a diplomatic instrument. By collaborating on PV–BESS integration, both countries enhance their standing in multilateral platforms such as the G20, ASEAN+3, and UNFCCC negotiations. Indonesia positions itself as a credible leader in Southeast Asia's energy transition, while South Korea consolidates its role as a technology provider and responsible climate actor in the Indo-Pacific (Kim, 2021). This cooperative framework demonstrates that the integration of solar PV and BESS is not only a technical solution but also a strategic pathway where science, economics, and diplomacy intersect.

Implications for Indonesia's Energy Transition. The integration of solar photovoltaic (PV) and battery energy storage systems (BESS) within Indonesia's energy framework carries profound implications for the country's transition towards a sustainable and resilient power sector. From a technical perspective, large-scale deployment of PV–BESS systems demonstrates the capacity to reduce dependency on coal—which accounted for over 66% of Indonesia's electricity generation in 2023—while stabilizing grid operations vulnerable to intermittency (IESR, 2023). Modeling results presented in Section 4.2 suggest that 10 GWp of PV capacity, integrated with BESS storing 25% of daily output, could displace up to 10% of peak-hour fossil generation, representing a major contribution toward Indonesia's renewable energy target of 23% by 2025 under the National Energy Policy (RUEN, 2023). Technically, this also contributes to tens of millions of tons of CO_2 emission reduction annually, aligning with Indonesia's Nationally Determined Contribution (NDC) commitments under the Paris Agreement.

Beyond technical gains, the implications are deeply institutional and international. Indonesia's cooperation with South Korea provides a concrete framework for accelerating PV–BESS integration. South Korea's leadership in battery technology and Indonesia's abundant natural resources—particularly nickel reserves critical for lithium-ion battery production—form a symbiotic relationship that embodies liberal interdependence (Keohane & Nye, 1977). The establishment of the Hyundai–LG Energy Solution USD 1.1 billion EV battery cell factory in Karawang not only strengthens Indonesia's domestic supply chain but also creates spillover effects in workforce upskilling, R&D collaboration, and the development of localized technology clusters (Tempo, 2023). Such industrial synergy directly enhances Indonesia's ability to deploy BESS domestically at scale, while ensuring South Korea secures access to strategic mineral resources (IEA, 2022).

Financially, bilateral and multilateral mechanisms provide additional leverage. Indonesia's participation in the Just Energy Transition Partnership (JETP, 2023), which mobilizes USD 20 billion in climate finance, creates opportunities to expand PV–BESS projects with international backing. South Korea's role as both investor and technology partner strengthens Indonesia's bargaining power in attracting concessional finance, reducing reliance on state budgets, and fostering private sector participation (World Bank, 2023). It illustrates that PV–BESS integration cannot be separated from financial diplomacy and institutional reforms, including revising local content regulations, incentivizing independent power producers (IPPs), and aligning policies with global investment norms.

Strategically, the implications extend to Indonesia's role in regional and global energy diplomacy. By advancing PV–BESS integration in partnership with South Korea, Indonesia enhances its credibility in multilateral forums such as the G20, ASEAN+3, and UNFCCC. The partnership demonstrates a concrete case of mutual benefit cooperation in energy transition, reflecting liberal institutionalist assumptions that states can achieve collective gains through rule-based cooperation (Keohane, 1984). For Indonesia, this translates into stronger leadership in Southeast Asia's renewable agenda, while South Korea consolidates its global reputation as a green technology provider. Together, both countries set a model for how bilateral cooperation in clean energy can contribute to global climate objectives, balancing technical feasibility, financial viability, and diplomatic legitimacy.

Implications for South Korea. South Korea's involvement in Indonesia's solar PV and Battery Energy Storage System (BESS) projects carries strategic implications for its broader energy transition and industrial positioning. As a global leader in advanced battery technologies, South Korea—through companies such as LG Energy Solution, Samsung SDI, and Hyundai Energy Solutions—has consistently sought to expand its technological footprint abroad (Kim, 2022). By investing in Indonesia's renewable energy sector, South Korea not only gains access to a rapidly growing energy market but also secures long-term opportunities for its domestic industries in manufacturing, R&D, and green technology exports. It reflects South Korea's national strategy to strengthen its clean energy leadership, as emphasized in the Korean Green New Deal (Government of Korea, 2020).

Moreover, cooperation with Indonesia provides South Korea with critical access to raw materials essential for battery production. Indonesia possesses one of the world's largest reserves of nickel—an indispensable component of lithium-ion batteries (IEA, 2021). By deepening its partnership, South Korea ensures greater security of supply chains and reduces vulnerability to global resource competition, particularly against China, which currently dominates the battery value chain (Park, 2023). This strategic move aligns with South Korea's broader energy security agenda, where diversifying supply chains is considered vital to sustaining industrial competitiveness in the EV and storage sectors (Lee, 2021).

At the geopolitical level, collaboration with Indonesia enhances South Korea's diplomatic influence in Southeast Asia. Through renewable energy partnerships, South Korea positions itself as a trusted partner in ASEAN's green transition, thereby strengthening its New Southern Policy (Moon, 2017). It creates a multidimensional benefit: South Korea advances its technological leadership, safeguards critical supply chains, and expands its international standing as a green economy leader. The bilateral partnership thus exemplifies a mutually beneficial relationship, where South Korea supports Indonesia's decarbonization goals while simultaneously reinforcing its own strategic and economic priorities.

Challenges and Barriers in PV–BESS Deployment. Despite the promising potential of integrating solar photovoltaic (PV) and Battery Energy Storage Systems (BESS) within the Indonesia–South Korea cooperation framework, several challenges remain that could hinder large-scale deployment. These barriers are multidimensional, spanning technical, economic, institutional, and social dimensions, which require coordinated solutions to ensure long-term sustainability.

Table 2. Challenges

Opportunities	Barriers
Reduced reliance on fossil fuels	High upfront costs
Improved energy security	Grid integration challenges
Emissions reductions	Lack of financial incentives
Innovation and economic growth	Regulatory and policy hurdles

From a technical perspective, intermittency and variability of solar resources continue to pose challenges for grid integration. While BESS offers a partial solution by smoothing fluctuations, storage systems face limitations related to degradation rates, lifecycle efficiency, and high replacement costs (Luo et al., 2015). Moreover, Indonesia's grid infrastructure remains underdeveloped, particularly in remote islands where renewable energy would be most impactful. Weak transmission capacity and limited interconnection constrain the integration of large-scale PV projects, leading to curtailment risks and inefficiencies (IEA, 2022).

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Economic barriers further exacerbate the problem. The initial capital cost of PV–BESS systems remains high relative to conventional coal generation, which continues to benefit from long-standing subsidies and guaranteed power purchase agreements (Kusumadewi & Kim, 2021). Although long-term cost trajectories for solar and storage are declining, investors face uncertainty in recovering capital expenditure due to regulatory risks and fluctuating tariff policies. Financing remains concentrated in donor-driven mechanisms such as the Just Energy Transition Partnership (JETP), while private capital mobilization is still limited (ADB, 2023).

Institutionally, Indonesia faces policy inconsistency and bureaucratic hurdles that delay project implementation. Local content requirements (TKDN) often increase costs and complicate procurement processes, while overlapping regulations between central and regional governments create additional uncertainty (Suharto, 2020). On the South Korean side, while companies are eager to invest, a lack of clear bilateral regulatory frameworks for joint ventures and intellectual property protection may limit the pace of cooperation.

Social challenges are also notable. Public acceptance of solar and BESS projects remains low in certain regions due to limited awareness, land acquisition disputes, and competing land-use priorities, especially in densely populated areas of Java (Nasution et al., 2022). Moreover, the shortage of skilled human resources in renewable energy engineering and storage technology constrains the ability to sustain projects over the long term, necessitating greater investment in education and training.

In summary, while the technical feasibility of PV–BESS integration is evident, realizing its full potential requires overcoming structural challenges across multiple domains. Addressing these barriers through coordinated policies, financial innovation, and capacity building will be essential for ensuring that the Indonesia–South Korea cooperation delivers not only technological benefits but also long-term resilience and sustainability.

Bilateral Cooperation Framework: Indonesia–South Korea. The cooperation between Indonesia and South Korea in advancing solar PV and Battery Energy Storage Systems (BESS) integration illustrates a multi-layered framework that combines state diplomacy, industrial collaboration, and multilateral engagement. At the state-to-state level, both governments have signaled a strong commitment to renewable energy development and carbon neutrality. Indonesia has pledged net-zero emissions by 2060, while South Korea targets 2050, and bilateral dialogues—such as the Indonesia–Korea Energy Forum—have provided platforms to align policy directions and investment priorities (MOTIE Korea, 2022; ESDM Indonesia, 2023). These alignments are consistent with the concept of complex interdependence outlined by Keohane and Nye (2012), where states increasingly rely on cooperation across multiple sectors rather than unilateral action.

At the industry-to-industry level, corporate actors have become key enablers of bilateral energy cooperation. A prime example is the USD 1.1 billion investment by Hyundai Motor Group and LG Energy Solution in establishing Indonesia's first electric vehicle (EV) battery cell factory in Karawang. This project not only strengthens Indonesia's industrial capacity in energy storage but also anchors South Korea's global supply chain strategy in the ASEAN region (Financial Times, 2024). Samsung SDI and other Korean firms have also expressed interest in expanding battery and smart grid technologies, positioning themselves as technological leaders capable of transferring know-how to Indonesian partners. Such cooperation demonstrates the growing role of transnational corporations in shaping the political economy of clean energy (Oatley, 2019).

At the multilateral and institutional level, Indonesia–South Korea collaboration is reinforced by global financing frameworks. The Just Energy Transition Partnership (JETP), launched in 2023 with a pledged value of USD 22 billion, offers a platform for channeling concessional loans, private capital, and climate funds into renewable energy projects (JETP, 2023). South Korea, as an OECD member and active contributor to climate finance, plays a strategic role in mobilizing support for Indonesia's transition. In addition, institutions such as the Green Climate Fund and the Asian Development Bank (ADB) provide co-financing mechanisms that strengthen bilateral projects while aligning with broader international climate governance (Hale, 2020).

From a theoretical perspective, the bilateral cooperation framework reflects the principles of international political economy (IPE), in which power, markets, and institutions interact to shape policy outcomes (Gilpin, 2001). In this context, Indonesia benefits from technology transfer, capacity building, and investment inflows, while South Korea secures strategic access to resources and strengthens its renewable technology markets. The interdependence thus produces mutual gains consistent with liberal institutionalist thought, where cooperation is facilitated by shared interests, formal institutions, and long-term strategic alignment (Keohane, 1984).

Opportunities for Regional and Global Cooperation. While challenges remain, the Indonesia–South Korea cooperation on PV–BESS deployment also creates significant opportunities to expand collaboration at both the regional and global levels. Such cooperation extends beyond bilateral ties, offering pathways for ASEAN-wide integration, global technology transfer, and the advancement of international climate goals. At the regional level, ASEAN provides a promising framework for renewable energy cooperation. Initiatives such as the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016–2025 emphasize the importance of cross-border power trade and the development of regional interconnection through the ASEAN Power Grid (ASEAN Centre for Energy, 2021). The integration of solar PV and BESS technologies into Indonesia's grid, supported by South Korean expertise, could serve as a model for neighboring countries such as Vietnam, Thailand, and the Philippines. It would not only strengthen energy security within the region but also accelerate progress toward ASEAN's renewable energy target of 23% by 2025.

From a global perspective, cooperation in PV–BESS also aligns with the objectives of the Paris Agreement and the UN Sustainable Development Goals (SDGs). Technology transfer and capacity-building initiatives fostered through bilateral projects can be scaled into multilateral platforms such as the International Solar Alliance (ISA) and Mission Innovation (UNFCCC, 2020). By engaging in these global frameworks, Indonesia and South Korea enhance their credibility as climate leaders, while simultaneously unlocking access to climate finance, carbon markets, and international investment flows.

Economic opportunities are equally significant. Indonesia's abundant nickel reserves, essential for lithium-ion battery production, position the country as a strategic supplier within the global energy transition supply chain (IEA, 2021). South Korean firms, already global leaders in EV and BESS technologies, benefit from securing stable raw material supplies while diversifying their markets in Southeast Asia. It creates a mutually reinforcing partnership in which Indonesia strengthens its role as a key player in the global clean energy economy, while South Korea consolidates its technological leadership and industrial competitiveness.

Diplomatically, this cooperation enhances soft power and strengthens regional stability. By spearheading joint renewable energy initiatives, Indonesia and South Korea contribute to building norms of cooperative energy governance in the Indo-Pacific. It stands in contrast to competitive energy geopolitics centered on fossil fuels, offering instead a model of liberal institutionalism where states achieve mutual gains through technological and financial collaboration (Keohane, 1984). Thus, PV–BESS cooperation serves not only as an instrument for energy transition but also as a platform for fostering regional trust, reducing energy insecurity, and reinforcing multilateral climate diplomacy.

In conclusion, regional and global opportunities arising from Indonesia–South Korea cooperation on PV–BESS extend well beyond bilateral benefits. They encompass energy security, economic integration, climate leadership, and international diplomacy, thereby amplifying the strategic significance of this partnership in advancing the global energy transition.

Policy Recommendations. The integration of solar photovoltaic (PV) and Battery Energy Storage Systems (BESS) within the Indonesia–South Korea cooperation framework requires targeted and evidence-based policy recommendations. Drawing on theories of policy transfer (Dolowitz & Marsh, 2000) and liberal institutionalism (Keohane, 1984), the following recommendations emphasize both domestic reforms and bilateral/multilateral enablers:

1. Regulatory and Institutional Reform in Indonesia. Indonesia's regulatory framework for renewable energy remains fragmented and often contradictory. For instance, the current local content requirement (TKDN)

of 40% for solar modules has deterred foreign investors and slowed project deployment (IESR, 2023). A revised framework should:

- Reduce TKDN requirements to 20% in the short term, while gradually building domestic manufacturing capacity through joint ventures with Korean firms.
- Establish a Renewable Energy Independent Authority (REIA) to coordinate inter-ministerial responsibilities and ensure transparent permitting.
- Adopt a bankable feed-in tariff (FiT) or auction system that guarantees price certainty for investors, aligning with international best practices (IRENA, 2022).
- It aligns with the institutional capacity-building theory (North, 1990), which suggests that strong institutions are necessary to enable efficient market outcomes.

2. Incentivizing Solar PV–BESS Deployment. Technical modeling in this study shows that deploying 10 GWp of solar PV with 25% BESS integration could generate approximately 12 TWh annually while mitigating intermittency. To operationalize this:

- Provide tax holidays and accelerated depreciation schemes for solar + BESS investments.
- Implement net-metering 2.0, where prosumers are credited at near-market rates for exported electricity, increasing rooftop PV uptake.
- Create dedicated green financing instruments, such as green bonds or blended finance mechanisms under JETP, to fund BESS installations at scale.
- These measures reflect the market-shaping role of the state (Mazzucato, 2018), where public intervention catalyzes private innovation and investment.

3. Technology Transfer and Industrial Collaboration with South Korea. South Korea's competitive advantage in advanced battery technology should be leveraged to accelerate Indonesia's energy transition. Policy actions include:

- Formalizing technology transfer agreements tied to joint industrial projects, ensuring skill development for Indonesian engineers.
- Establishing an Indonesia–Korea Renewable Energy Innovation Hub focused on R&D in grid-scale storage and high-efficiency solar modules.
- Incorporating intellectual property (IP) sharing clauses within bilateral agreements to avoid dependency traps and foster domestic innovation.
- It follows the policy transfer framework (Stone, 2017), emphasizing the adaptation of best practices to local conditions rather than wholesale adoption.

4. Strengthening Bilateral and Multilateral Governance. Bilateral cooperation should be embedded within wider multilateral frameworks to ensure sustainability and credibility. Key recommendations include:

- Aligning Indonesia–Korea projects with JETP investment plans, ensuring concessional loans are tied to measurable emission reduction outcomes.
- Encouraging South Korea to channel Official Development Assistance (ODA) and Green Climate Fund (GCF) resources specifically into PV–BESS projects
- Creating a joint monitoring mechanism to assess performance, modeled after the OECD's peer review system, ensuring accountability and transparency.
- This approach resonates with liberal institutionalism, where international cooperation reduces transaction costs and builds trust among stakeholders.

5. Political Feasibility and Long-Term Strategy. Finally, recommendations must consider political realities. Given Indonesia's coal dominance and vested interests, phased implementation is essential:

- Short term (2025–2030): Pilot 2–3 GW PV–BESS projects with Korean partners under blended finance.
- Medium term (2030–2040): Scale up to 25–30 GW, with 30% local manufacturing participation.
- Long term (2040–2060): Achieve the 108 GW solar target with integrated BESS, fully aligned with Indonesia's net-zero pathway.

CONCLUSION

This study set out to examine Indonesia's persistent reliance on fossil fuels and the underutilization of its vast solar energy potential, situating the analysis within the context of Indonesia–South Korea cooperation. The problem was framed around three central questions: (1) the extent to which fossil fuel dominance and the limited uptake of solar PV hinder Indonesia's energy transition, (2) how mathematical integration of solar PV with Battery Energy Storage Systems (BESS) could improve reliability of the national power system, and (3) the strategic role of bilateral cooperation with South Korea in realizing such integration.

Methodologically, the research employed a multidisciplinary approach, combining applied mathematics, energy system modeling, and international relations analysis. A scenario of deploying 10 GWp of solar PV capacity with 25% BESS integration was mathematically modeled, yielding an estimated annual generation of 12 TWh. The storage component significantly mitigates intermittency, improving grid reliability and reducing coal dependency. On the qualitative side, the study analyzed policy documents, bilateral agreements, and international cooperation frameworks through the lens of international political economy and energy diplomacy.

The findings reveal three major insights. First, fossil fuel dominance—particularly coal, which accounts for over 60% of electricity generation—remains a structural barrier to Indonesia's clean energy transition. Despite an estimated technical potential of more than 3,000 GW of solar, only 0.02% has been utilized, demonstrating the gap between ambition and realization. Second, the integration of PV–BESS provides a technically feasible solution to intermittency, offering measurable contributions to emission reduction and grid stability. Third, international cooperation, especially with South Korea, emerges as a catalytic enabler. Korea's technological leadership in battery manufacturing, its industrial investments in Indonesia, and its shared net-zero target by 2050–2060 provide a strong foundation for technology transfer, joint innovation, and policy reform.

In sum, the study concludes that Indonesia's energy transition depends on both domestic reforms and international collaboration. Technically, scaling up PV–BESS integration could deliver tangible reliability and decarbonization benefits. Institutionally, cooperation with South Korea strengthens Indonesia's capacity for industrial upgrading, financing, and energy diplomacy. The contribution of this research lies in bridging three analytical domains—applied mathematics, energy systems, and international relations—thereby demonstrating that Indonesia's transition to a low-carbon energy future is not only a question of technical feasibility, but also of institutional design and international partnership.

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