Beyond coal: optimization of hybrid floating PV–hydropower systems for Indonesia's decarbonization

Firsta Zukhrufiana Setiawati[1,3], Tania June[1], Muh Taufik[1,4], Rudi Kurnianto[2]
[1]Department of Geophysics and Meteorology, IPB University, Bogor, Indonesia
[2]Department of Electrical Engineering, Tanjungpura University, Pontianak, Indonesia
[3]Indonesian Agency for Meteorology, Climatology, and Geophysics Agency, Jakarta, Indonesia
[4]Centre for Environmental Research, Campus IPB Dramaga, IPB University, Bogor, Indonesia

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ABSTRACT

Indonesia's failure to meet the 23% renewable energy target, resulting in continued reliance on fossil fuels, necessitated a multi-criteria evaluation of hybrid energy systems. This study aimed to simultaneously minimize the levelized cost of energy (LCOE), reduce carbon dioxide (CO_2) emissions (decarbonization), and maximize the renewable energy penetration by integrating a coal-fired power plant (coal), hydroelectric power plant (hydro), and floating photovoltaic (FPV) power plant at sites in western Java (West Java and Banten provinces). Thirteen configurations were evaluated using European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 climate data (1991-2020) and hybrid optimization of multiple energy resources professional (HOMER Pro) simulations. The optimal coal-hydro-FPV-Li-Ion hybrid configuration achieved 91.1% renewable energy penetration, 94.5% decarbonization, avoided ~4.1 million kg CO_2 annually, delivered an LCOE of $0.1201/kWh with an internal rate of return (IRR) of 7.6%, return on investment (ROI) of 5.9%, and payback period of 8.7 years. This configuration outperformed the pumped hydro storage alternative, demonstrating 38% lower capital expenditure (CAPEX) and 49% faster payback period, confirming its economic suitability for Indonesia's fiscal constraints. These findings indicate that a hybrid energy system with battery storage technology is a technically and economically viable pathway toward Indonesia's decarbonization agenda.

Corresponding Author:

Tania June
Department of Geophysics and Meteorology, IPB University
Street Meranti Wing 19 Level 4, Dramaga District, Bogor Regency, West Java 16680, Indonesia
Email: taniajune@apps.ipb.ac.id

1. INTRODUCTION

Indonesia's increasing population, technological, and industrial development demands higher electrical energy consumption [1], [2]. Nevertheless, electricity generation maintains a strong reliance on fossil fuels [3], which contributes to increasing carbon emissions and environmental damage [4]. Yet, fossil energy remains widely used because it is more economically favorable [5]. The Indonesian government has long established strategies to manage this challenge, but realizing renewable energy targets has proven difficult [6]. The national energy mix target of 23% by 2025 was not realized, yielding only 11.31% in 2020 [7] and ~17% in 2025 [8]. Indonesia's commitments under the Nationally Determined Contribution (NDC) and Sustainable Development Goals (SDGs) [9], [10], further derived into national and regional regulations [11], define the urgency of achieving green energy. However, the development of Indonesia's energy mix has not yet reached the set target [12], motivating this study to explore Indonesia's abundant renewable energy potential [13].

Hybrid energy systems that integrate renewable and conventional energy sources have been extensively studied as a means of accelerating the energy transition [14]. Existing studies demonstrate the technical and economic viability of various hybrid configurations, such as solar-wind [15], solar-hydro [16], and wind-hydro [17] systems. However, most studies focus on minimizing costs or maximizing renewable energy penetration, without simultaneously considering technical, economic, and environmental specifically climatic aspects [18]. Furthermore, studies integrating long-term climate data, particularly reanalysis datasets such as the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5), into the optimization of hybrid energy systems remain limited [19]. In the specific context of Indonesia, comprehensive multi-aspect optimization studies on hybrid energy systems have not yet been conducted [20]. This study bridges this gap by optimizing hybrid energy systems combining fossil and renewable sources across technical, economic, and environmental aspects using 30 years of ERA5 reanalysis climate data.

This research focuses on Western Java, integrating the hydroelectric power plant (hydro) and floating photovoltaic (FPV) in Cirata as renewable energy sources with the coal-fired power plant (coal) in Serang as baseload and backup to manage the intermittent nature of renewable generation. This study contributes to three specific areas of the existing literature: (i) a techno-economic optimization framework integrating hydropower, FPV, and fossil generation analyzed using 30 years of reanalysis data; (ii) an Indonesia-specific case study at power plants located in West Java and Banten provinces; and (iii) a decarbonization assessment in line with Indonesia's zero emissions targets. To address the contributions, the objective of this study was to simultaneously examine the system efficiency, decarbonization potential, and economic viability, providing a scalable framework to support Indonesia's energy transition.

2. METHOD

2.1. Site location

The research sites are located in the provinces of West Java and Banten (Indonesia), at three power generation sites, namely: Cirata hydroelectric power plant (hydro), Cirata FPV power plant, and coal-fired power plant (coal). The hydro and FPV are located in the similar area (specifically at Cirata reservoir), and the hydro power plant has operated since the 1990s [21]; the FPV was subsequently built by utilizing the reservoir surface and came into operation in late 2023 [22]. The hydroelectric power plant has a capacity of 1008 MW and the FPV 192 MWp, both of which are on-grid systems whose power output is directly distributed to the Java-Bali grid [23]. The subsequent electricity distribution system is managed by Indonesia's state-owned electricity company as both power plants operate without energy storage systems [23]. The third site is a coal power plant located in Serang, Banten; the three research sites are illustrated in Figure 1. These sites were selected due to their strategic role in Indonesia's electricity supply and their suitability for hybrid renewable energy integration.

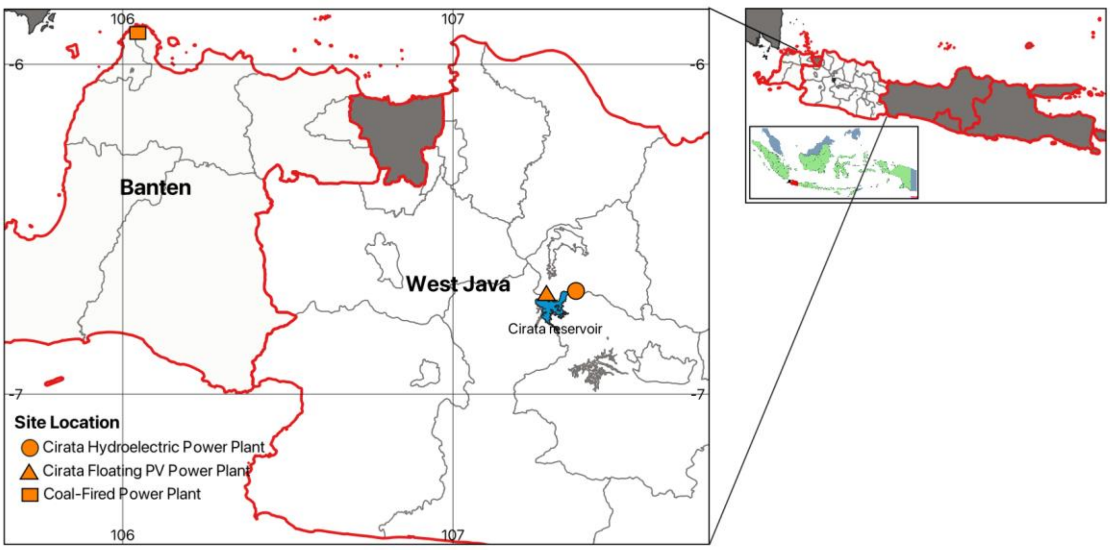


Figure 1. Study sites showing three power generation plants in West Java and Banten provinces, Indonesia

This study simulated a hybrid system between renewable and non-renewable (conventional) energy sources. The research sites for renewable energy sources are represented by Cirata hydro and FPV, while non-renewable or fossil-fuelled energy sources comprise the coal power plant. The coal served as baseload to maintain system stability and has a capacity of 2×1,000 MW units operating as an on-grid system that is distributed directly to the Java-Bali grid. Although modern coal power plants incorporate cleaner combustion technologies, decarbonization remains a critical consideration for the coal given its reliance on coal as the primary fuel. The integration of these three power plants represents Indonesia's ongoing energy transition, where variable renewable energy was progressively integrated with conventional generation infrastructure to achieve national energy mix targets. Site selection considered the geographical representation of the Java-Bali electricity system as the national electricity backbone [24].

2.2. Climate characteristics of site location

The renewable energy components of this study are significantly affected by climatic parameters. The northern coastal region, including the coal power plant site in Serang, tends to have lower rainfall than the mountainous central region of West Java [25]. Cirata hydro and FPV power plant sites, located in the central mountainous region, receive higher annual rainfall, approximately 2,000-3,000 mm per year. This topographical difference creates a rainfall gradient [26], which affects the operational characteristics of each power plant. The results of the Mann-Kendall test to assess long-term climatic trends around the study area are presented in Table 1.

Climatic conditions across the three sites showed a statistically significant increase in surface temperature of 0.02-0.03 °C per year as confirmed by the p-value < 0.001. Meanwhile, rainfall and solar radiation showed no significant trend (p-value > 0.05). Rainfall and solar radiation were variable rather than showing long-term changes. Cross-site comparison indicated that hydro and FPV had almost identical climatic characteristics due to their co-location at the same reservoir, while coal exhibited minor variations due to its lower coastal elevation. These climatic conditions have important implications for hybrid system planning, as increasing temperatures affect the efficiency of FPV solar panels [27], [28] and high rainfall variability requires hydro operational flexibility to manage dry periods [29].

Table 1. Mann-Kendall test results for climate parameters (1991-2020) around the study site

Parameter	Hydro	FPV	Coal
Rainfall (mm)			
MK-stat	-57	-98	-65
p-value	0.318	0.301	0.254
Slope	-12.05	-11.95	-8.80
Significance	No	No	No
Surface temperature (°C)			
MK-stat	220	228	263
p-value	< 0.001	< 0.001	< 0.001
Slope	0.03	0.03	0.02
Significance	Yes	Yes	Yes
Solar radiation (kWh/m^2)			
MK-stat	23	-47	17
p-value	0.393	0.643	0.775
Slope	0.73	0.76	0.51
Significance	No	No	No

Note: positive MK-stat indicates increasing trends, and vice versa. Significance at $\alpha = 0.05$

2.3. Data and inputs

This study utilized climate data of rainfall, surface air temperature, and solar radiation parameters. We derived these parameters from ECMWF ERA5 data for the period 1991-2020 extracted according to the respective power plant locations (details are shown in Table 2). This study selected ERA5 data due to their consistent temporal coverage, high spatial resolution, and suitability for long-term renewable energy assessment. The technical and economic specifications of each plant were presented in Table 2, and the energy source data were presented in Table 3. Cirata hydro was modelled with a head height of 233.53 m and a design flow rate of 500,000 L/s. The system operated with a turbine efficiency of 88% and included pipe head losses. Cirata FPV used a tilt angle of 6.68° with an inverter efficiency of 98%, and a temperature coefficient of -0.4%/°C to account for the effect of temperature on panel performance.

The energy inputs applied in the simulation comprised an annual solar global horizontal irradiance (GHI) of 4.61 kWh/m²/day, and an average hydro flow rate of 287,833 L/s. The temporal profiles of these resources, including the load profile (Figure 2), rainfall profile (Figure 3(a)), and solar radiation profile (Figure 3(b)), were also incorporated as simulation inputs. Coal was configured with a lower heating value

(LHV) of 15.5 MJ/kg, 40% efficiency, and used ultra super critical (USC) technology with a minimum load ratio of 40% [30] and a minimum runtime of 480 minutes. The Li-Ion battery was modelled using a generic 1 MWh module with a roundtrip efficiency of 90%, initial state of charge of 100%, and minimum state of charge of 50%, with a search space of up to 200 MWh. The pumped hydro storage (PHS) was modelled using a generic 245 kWh pumped hydro module with a search space of up to 6,125 MWh, initial state of charge of 100%, and minimum state of charge of 0%. Supporting data such as water discharge, hydro-FPV-coal specifications were obtained from Indonesia's state-owned electricity company.

Table 2. Technical and economic parameter of power plants

Parameter	Unit	Hydro	FPV	Coal	Li-Ion	PHS
Coordinates		6.70°S, 107.36°E	6.70°S, 107.37°E	6.05°S, 106.07°E		
Installed capacity		1008 MW	145 MW (192 MWp)	2×1,000 MW		
Capital cost	$	2,016,000	1,500,000	2,400,000		
Efficiency	%	88	21	43		
Derating factor	%	-	88	-		
Min. load ratio	%	-	-	40		
O&M cost	$/year	30,240,000	3,840,000	31,500,000		
Fuel price	$/m^3	-	-	130		
CO_2 content	%	-	-	85		
Lifetime	years	25	25	25	15	7
Storage capacity	MWh				200	6125
Roundtrip efficiency	%				90	90
Min. state of charge	%				50	0
Max. state of charge	%				100	0

Table 3. Energy resources

Parameter	Unit	Value
Energy resources		
Annual solar GHI (avg.)	kWh/m^2/day	4.61
Annual hydro flow rate (avg.)	L/s	287,833
Lower coal heating value	MJ/kg	15.5

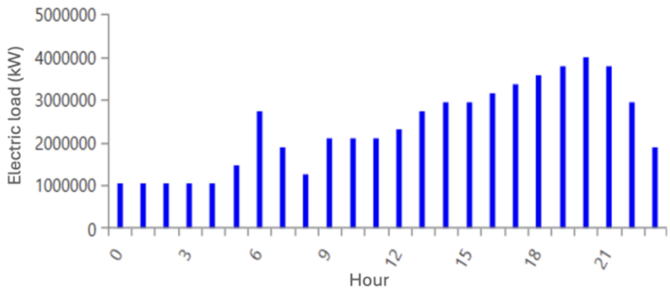
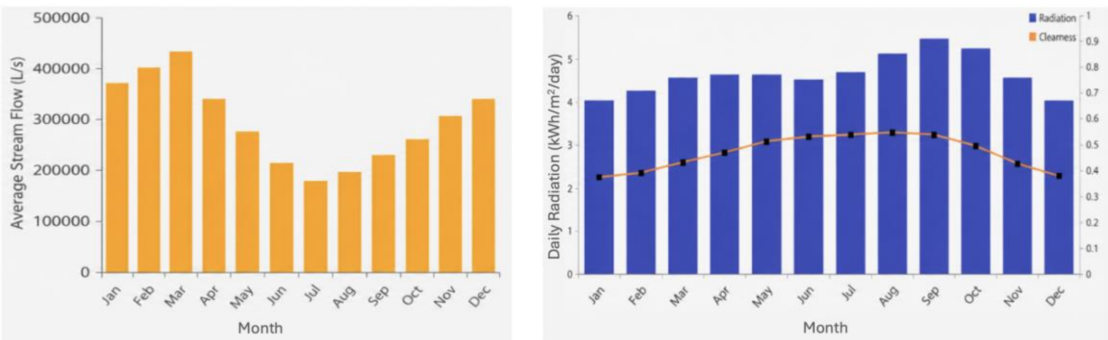


Figure 2. Load profile



(a) (b)

Figure 3. Renewable resource profiles used in the simulation: (a) average streamflow for hydropower and (b) daily solar radiation and clearness index for FPV

The load profile (Figure 2) used in the simulation represented provincial-scale electricity consumption based on aggregated statistical demand patterns with a peak load of 338 MW and an average load of 104 MW, comprising residential, industrial, and commercial sectors. The peak load occurred at night (6-9 pm), while the minimum load in the early morning (3-5 am) was 49 MW. The system load factor of 31% with an energy demand of approximately 907 GWh/year reflected a predominantly residential load profile. The evening peak character provided dispatch optimization opportunities for hydro, while daytime load could utilize FPV generation. The minimum to peak ratio of 14.5%, which is classified as low, indicated the need for an energy storage system in a hybrid energy system configuration. This load profile formed the basis for the integration and sizing strategy of system components in the hybrid energy system [31], which was simulated in this study. The characteristics of renewable resources, in the form of river flow for hydro and solar radiation for FPV, were shown in Figure 3 as the main input for renewable energy generation components in the system configuration.

The river flow profile used in the simulation data (Figure 3(a)) for the hydro component showed a clear seasonal pattern with an average discharge of approximately 150,000-450,000 L/s throughout the year. The highest discharged occurred during December-March (coinciding with the wet season in the Cirata region), while the lowest was during June-August, coinciding with the dry season [32]. This seasonal pattern indicated that the availability of hydro energy fluctuated throughout the year. Meanwhile, solar radiation (average 4.5-5.0 kWh/m^2/day) and clearness index (0.45-0.50) shown in Figure 3(b) were relatively stable (small fluctuations) throughout the year and atmospheric conditions were favourable for solar energy generation. The complementary characteristics of high-water resource availability in the wet season and highly stable solar resource provided advantages for the dispatch optimization of the hybrid system in hybrid optimization of multiple energy resources professional (HOMER Pro) simulation.

2.4. Optimization framework

The hybrid system simulation was performed using HOMER Pro Microgrid x64 3.14.2 to determine the optimal operational configuration of the three power plants, based on net present cost (NPC) minimization [33]. HOMER Pro utilizes a thorough search algorithm via HOMER Optimizer^{TM} that systematically evaluates all feasible system configurations and ranks them according to minimum NPC. The decision variables considered in this optimization (Table 4) include: (i) system configuration comprising integration of hydro, FPV, coal, Li-Ion battery or PHS; (ii) capacity sizing of storage components, treated as continuous search space to allow HOMER Optimizer^{TM} to determine the optimal sizing for each configuration; and (iii) dispatch strategy, evaluated under load following (LF), cycle charging (CC), and combined LF+CC strategies. The optimization objective was to minimize the NPC, from which the levelized cost of energy (LCOE) was subsequently derived as the primary economic performance indicator.

If the Coal served as baseload and the hydro-FPV adjust output according to resource availability and load fluctuations, the LF dispatch strategy is employed. The simulation also utilized a minimum renewable energy fraction constraint of 70% and an operating reserve of 15% of the annual peak load. The emission factor for CO_2 was set to 0 kg/MWh for hydro and FPV [34], and 13,566 g/m^3 of fuel for coal. Based on this framework thirteen hybrid energy system configurations combining coal, hydro, FPV, Li-Ion, and PHS were evaluated and compared across technical, economic, and climate-environmental aspects.

Table 4. Optimization settings

Parameter	Unit	Value
Project lifetime	Years	25
Discount rate	%	6.7
Constraint	-	Minimum renewable energy fraction 70%
Dispatch strategy	-	Combined LF and CC

2.5. Hybrid energy system design

This study evaluated thirteen hybrid energy system configurations representing a progressive transition from fossil-based to renewable-dominated systems to identify the optimal configuration for energy resources, decarbonization, technology and economics. The scenarios (Table 5) were designed to explore two fundamental system combinations: hybrid systems without storage (Sce1-Sce4) and those with storage (Sce5-Sce12). A conventional scenario (Sce0) is also included as a reference for comparative analysis of simulation results. Each configuration represented a realistic implementation considering technical feasibility, economic viability, and carbon emission reduction. This classification of configurations provided direction for a comprehensive assessment of how the use of storage technologies and energy mix affects system performance metrics. All scenarios (Table 5) were simulated under identical operational conditions based on the input resources in Tables 2 to 4.

Table 5. Configuration matrix of thirteen hybrid energy system scenarios evaluated in this study

ID	Configuration	Storage type	Category
Baseline			
Sce0	Coal	None	Conventional fossil fuel
Systems without storage			
Sce1	Coal-Hydro	None	Fossil-renewable hybrid (mix)
Sce2	Coal-FPV	None	Fossil-renewable hybrid (mix)
Sce3	Hydro-FPV	None	Fully renewable
Sce4	Coal-hydro-FPV	None	Fossil-renewable hybrid (mix)
Systems with storage			
Sce5	Coal-Hydro-Li-Ion	Li-Ion	Fossil-renewable hybrid (mix)
Sce6	Coal-FPV-Li-Ion	Li-Ion	Fossil-renewable hybrid (mix)
Sce7	Hydro-FPV-Li-Ion	Li-Ion	Fully renewable
Sce8	Coal-hydro-FPV-Li-Ion	Li-Ion	Fossil-renewable hybrid (mix)
Sce9	Coal-hydro-PHS	PHS	Fossil-enewable hybrid (mix)
Sce10	Coal-FPV-PHS	PHS	Fossil-renewable hybrid (mix)
Sce11	Hydro-FPV-PHS	PHS	Fully renewable
Sce12	Coal-hydro-FPV-PHS	PHS	Fossil-renewable hybrid (mix)

The configuration matrix (Table 5) shows a progressive integration scheme from fossil-based (conventional) energy generation toward a hybrid system with renewable energy penetration. Sce1-Sce4 served as benchmarks to evaluate energy integration without storage systems, thereby identifying intermittency and excess power management issues. Sce5-Sce12 incorporated storage systems (Li-Ion and PHS) to assess the effectiveness of storage systems through generation efficiency, economics, and decarbonization. Sce3, Sce7, and Sce11 excluded coal (i.e., fully renewable configurations); therefore, the system relied entirely on hydro and FPV. Sce4, Sce8, and Sce12 represented the most progressive integration scenarios that demonstrated resource diversification. All of these energy integration schemes were evaluated through the optimization of hybrid energy systems in accordance with the framework shown in Figure 4.

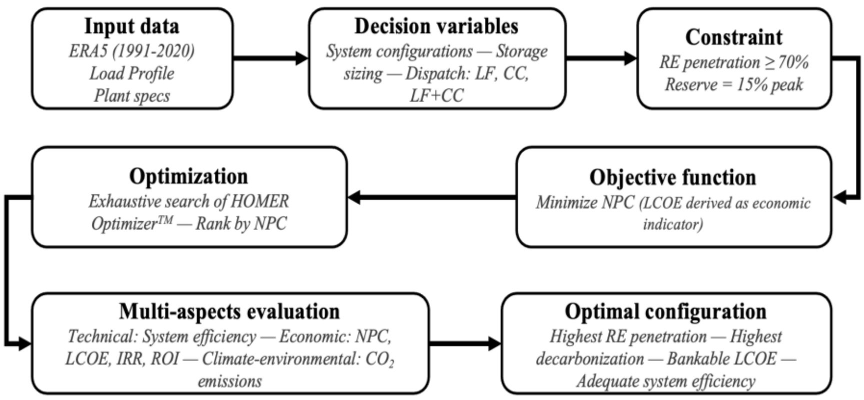


Figure 4. Optimization framework

3. RESULTS AND DISCUSSION

3.1. Multi-aspect performance analysis of hybrid configurations

HOMER Pro simulation results for one baseline configuration and twelve hybrid configurations consisting of a combination of coal, hydro, and FPV were summarised in Table 6. The evaluation examined technical performance (system efficiency), climate-environmental aspect (carbon emissions), and economic feasibility (NPC, capital expenditure (CAPEX), LCOE, and operational expenditure (OPEX)). Sce0 was used as a conventional fossil fuel baseline configuration, for carbon emission reference and was excluded from the ranking due to its position as a baseline. Sce3 was also excluded as fully renewable stand-alone system, since it was not feasible [35] and required grid connection (on-grid operation) or storage system as a possible option [36]. Each configuration was analyzed to identify the optimal scheme in the context of Indonesia's energy transition towards net zero emission. These results highlighted the trade-offs between cost efficiency, renewable penetration, and emission reduction across different hybrid system configurations.

Across the thirteen scenarios, systems with higher renewable penetration consistently reduced emissions but exhibited higher initial costs, while fossil-dominated configurations achieved lower capital costs at the expense of significantly higher emissions. In terms of technical performance, system efficiency showed large variations, ranging from 16% (Sce7, Sce11) to 95% (Sce6). Sce6 (coal-FPV-Li-Ion) achieved the highest efficiency of 95%, indicating approximately 5% energy curtailment, attributed to optimal resource utilization through fossil backup for baseload stability and Li-Ion battery for peak shaving. Meanwhile, the fully renewable configurations (Sce7 and Sce11) showed a low efficiency of 16%, due to the mismatch between the intermittent renewable generation profile, load, and insufficient storage capacity to capture excess power [33]. The higher efficiency in the fossil backup configuration (Sce1: 33%, Sce4: 33%, Sce6: 95%) indicated the ability of dispatchable generation to fill the gap when renewable energy production was low. Sce10 (coal-FPV-PHS) achieved 79% efficiency, higher than Sce8 (coal-hydro-FPV-Li-Ion), indicating that PHS was more effective for large-scale storage systems. These results demonstrated that achieving system efficiency above 50% for high renewable penetration configurations required a combination of adequate storage capacity and flexible backup generation [34].

Environmental analysis through CO2 emissions showed a decarbonization range from zero emission (fully renewable: Sce7 and Sce11) to 4.32 million kg/year (baseline Sce0). Sce7 and Sce11 achieved zero emissions, demonstrating the technical feasibility of a 100% renewable energy system with storage systems, but at the expense of system efficiency (16%). The configurations with Li-Ion batteries showed high decarbonization performance: Sce8 (coal-hydro-FPV-Li-Ion) with the lowest emissions of ~0.24 million kg/year (94.5% decarbonization vs. baseline); Sce5 (coal-hydro-Li-Ion) with emissions of approximately ~0.30 million kg/year (93% decarbonization). Sce1 (coal-hydro) and Sce4 (coal-hydro-FPV) showed moderate emissions of approximately ~0.9 million kg/year (79% decarbonization). Meanwhile, the highest efficiency Sce6 (coal-FPV-Li-ion) produced higher emissions of approximately ~1.31 million kg/year (69.6% decarbonization). Sce3 (fully renewable-on-grid) produced emissions that far exceeded the baseline at approximately ~55 million kg/year, due to high grid purchases from fossil-based power grids. These results demonstrated that CO2 emission reductions of above 90% could be achieved with hybrid systems incorporating Li-Ion battery storage (Sce5 and Sce8), aligning with the NDC target of 43.2% conditional emission reduction by 2030 and its commitments under the Paris Agreement toward net zero emission by 2060.

Economic aspects were evaluated using NPC, CAPEX, LCOE, and OPEX metrics. The LCOE of Sce7 (hydro-FPV-Li-Ion) reached the lowest value of $0.082/kWh, competitive with the tariff of Indonesia's state-owned electricity company (~$0.09/kWh) [37], followed by Sce5 (coal-hydro-Li-Ion) and Sce8 (coal-hydro-FPV-Li-Ion) at ~$0.120/kWh. The baseline configuration had the highest LCOE of $0.2995/kWh, confirming the non-competitiveness of pure coal-based generation in lifecycle economics. Sce7 (hydro-FPV-Li-Ion) paradoxically showed a low CAPEX of ~$243 million while its efficiency was only 16%. Sce8 emerged as the optimal configuration by balancing economic feasibility, renewable energy integration, and emission reduction more effectively than other evaluated scenarios. Sce8 (coal-hydro-FPV-Li-Ion) demonstrated competitive results with an LCOE $0.1201/kWh a 60% reduction compared to the coal-based baseline (Sce0: $0.2995/kWh) CAPEX ~$938 million, the lowest OPEX ~$49 million/year, and an attractive NPC ~$1.70 billion, making it the most bankable configuration for Indonesia with low-cost financing. Sce12 (coal-hydro-FPV-PHS), with the same resource configuration but different storage, showed more expensive results: LCOE $0.1977/kWh, CAPEX ~$1 billion, OPEX ~$96 million/year, and NPC ~$2.80 billion. These results demonstrated that energy transition accompanied by storage systems was economically feasible and competitive, confirming that hybrid FPV-Hydro system could become economically viable under existing or planned renewable energy incentives in Indonesia.

Table 6. Performance metrics of hybrid configuration systems

ID	Eff.* (%)	CO_2 (kg/year)	NPC ($)	CAPEX** ($)	LCOE ($)	OPEX*** ($)	Information
Sce0	37	4,323,840	4,249,101,000	715,000,000	0.2995	184,627,172	Baseline
Sce1	33	922,280	1,930,413,000	717,016,000	0.1361	77,556,780	
Sce2	27	2,895,209	3,772,543,000	944,737,331	0.2659	180,745,000	
Sce3				no feasible solution			
Sce3+	86	55,731,082	1,944,261,000	253,243,885	0.0227	140,458,000	High emission
Sce4	33	905,995	2,225,262,000	937,409,350	0.1568	82,315,720	
Sce5	22	303,513	1,708,076,000	937,316,000	0.1204	49,264,710	
Sce6	95	1,314,986	2,086,583,000	936,437,864	0.1471	73,513,910	
Sce7	16	0	1,163,750,000	243,808,054	0.0822	58,800,000	
Sce8	21	238,681	1,703,794,000	938,453,864	0.1201	48,918,280	
Sce9	22	420,940	2,837,817,000	1,368,137,600	0.2000	93,937,540	
Sce10	79	668,998	33,137,810,000	1,601,369,415	0.2338	109,709,800	
Sce11	16	0	2,912,159,000	891,001,773	0.2064	129,186,400	
Sce12	18	424,395	2,804,455,000	1,299,545,477	0.1977	96,189,390	

Note: *system efficiency; ** CAPEX; *** OPEX; +fully renewable on grid-because of no feasible solution

3.2. Optimal system configuration

Identifying the optimal hybrid energy system requires simultaneous evaluation of multi-aspects [38]. To identify the optimal configuration, Sce8 (coal-hydro-FPV-Li-Ion) was comprehensively evaluated against Sce12 (coal-hydro-FPV-PHS) across economic, technical and climate-environmental aspects, using internal rate of return (IRR), return on investment (ROI), and simple payback, system efficiency, and decarbonization metrics (Table 7).

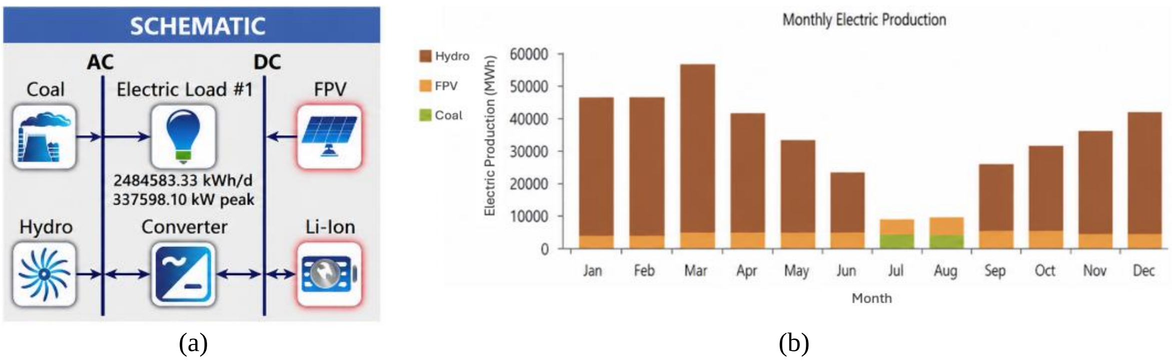
Table 7. Comparative performance of coal-hydro-FPV with Li-Ion and PHS storage

Parameter	Performance metric	Sce8 (coal-hydro-FPV-Li-Ion)	Sce12 (coal-hydro-FPV-PHS)
Economics	IRR (%)	7.6	6.1
	ROI (%)	5.9	4.4
	Simple payback (year)	8.7	13
Environment	Decarbonization (%)	94.5	90.2
Technical	System efficiency (%)	21	18

Climate-environmental performance of Sce8 was superior, with 4.3% higher decarbonization than Sce12 (Sce8: 94.5% vs. Sce12: 90.2%). System efficiency of Sce8 was 3% higher than Sce12 (Sce8: 21% vs. Sce12: 18%). The dominance of Sce8 in economic, climate-environmental, and technical aspects was attributed to the advantages of Li-Ion technology (lower cost, flexible operation, and faster response time) [39]. These results confirmed battery storage technology as the optimal solution for hybrid renewable systems [40], with particular relevance for Indonesia, with important implications for technology and policy priorities. Through systematic identification and analysis, Sce8 was determined to be the optimal hybrid system configuration, with the configuration shown in Figure 5.

In the Sce8 configuration (Figure 5(a)), the electricity flow is divided into alternating current (AC) and direct current (DC) lines integrated through a bidirectional converter. The Coal and Hydro plants generate electricity in AC form and are connected directly to the AC bus, enabling the generated energy to flow directly to the load without requiring conversion. The FPV generates electricity in DC form, connected to the DC bus along with Li-Ion batteries and must first be converted to AC via an inverter before supplying the load. The converter also operates as a rectifier during battery charging when excess energy is produced. This configuration optimized the utilization of renewable energy from Hydro and FPV while maintaining supply stability through Coal as baseload and Li-Ion battery as energy storage to absorb excess energy and release it during peak demand or reduced renewable production.

The monthly electricity production of Sce8 (Figure 5(b)) was dominated by Hydro as the main generation source, contributing 83.9% (~3.3 million MWh/year), followed by FPV at 14.1% (~563 thousand MWh/year), and Coal at 2.02% (~80 MWh/year). The seasonal pattern was apparent, with high production during the wet season (October-March) and reduced output during the dry season (April-September). FPV production increased during the peak dry season (July-August) to compensate for reduced Hydro availability, while Coal operated only during the dry season as backup. The system achieved a renewable energy penetration of 91.1%, demonstrating the effective integration of complementary renewable and fossil sources within the hybrid configuration, where coal served as a flexible backup to ensure system reliability while Hydro and FPV dominated energy generation.



(a) (b)

Figure 5. Simulation results of Sce8 configuration: (a) schematic of coal-hydro-FPV-Li-Ion hybrid energy system (Sce8) configuration and (b) monthly electricity production of Sce8 configuration

3.3. Discussion

The optimal configuration Sce8 (coal-hydro-FPV-Li-Ion) demonstrated an interesting trade-off between system efficiency of 21% and renewable fraction of 91.1%. This relatively low efficiency must be interpreted in the context of system characteristics with high renewable penetration [41], where excess generation rather than conventional energy losses is the primary driver of curtailment. The high energy curtailment of ~79% reflected the high excess power that could not be absorbed by the system due to mismatches between generation and load demand. This phenomenon was inherent in systems with a dominance of intermittent renewable sources [42], especially during high hydro production in the wet season when generation significantly exceeded load demand. However, this seasonal discrepancy was managed effectively through the complementary roles of coal, Li-Ion batteries, and a combined dispatch strategy.

The role of coal as a flexible backup, although its contribution was small (2.02%), proved important for maintaining the system stability and resilience during the peak dry season (June-August) when Hydro production reduced substantially a finding that highlights the continued relevance of dispatchable fossil backup in high-renewable hybrid system during transition periods. The integration of Li-Ion batteries, which have fast response times and high round-trip efficiency, allowed the system to perform peak shaving and load leveling optimally [43]. The combined LF and CC dispatch strategy enabled the system to adapt to seasonal production patterns [44], where Hydro operated as baseload during the wet season, while FPV and Li-Ion optimized daytime generation and evening peak demand through a time-shifting mechanism. Together, these operational characteristics explain why Sce8 achieved a high renewable penetration of 91.1% despite its relatively low system efficiency, highlighting that efficiency metrics alone are insufficient to evaluate hybrid renewable system performance.

The economic advantages of Sce8 reflected a viable pathway for implementing energy transition in Indonesia considering the financial constraints and urgency of decarbonization. The LCOE of $0.1201/kWh achieved by Sce8 was highly competitive with the average government tariff (~$0.09/kWh), reflecting the feasibility of developing hybrid energy systems in Indonesia. The simple payback period of 8.7 years fell within an acceptable range for infrastructure projects in Indonesia, considering the typical concession period for independent power producer (IPP) is 25-30 years [45], thus providing sufficient time for cost recovery and profit generation. The IRR of 7.6% was quite attractive for Indonesia's power generation sector when compared to government bond yields of ~6-7%. This economic indicator was further strengthened when compared to alternative storage configurations, particularly PHS.

Comparison with Sce12 (coal-hydro-FPV-PHS) revealed the limitations of PHS: 38% higher CAPEX and ~49% longer payback period, making PHS less bankable. This cost disadvantage of PHS can be attributed to its higher infrastructure requirements and longer construction timelines compared to Li-Ion battery systems. In the context of Indonesia's fiscal constraints, competing development priorities, and aggressive renewable energy targets (23% target in 2025 not achieved), Li-Ion storage technology offered a faster deployment and lower upfront investment [46], which fitted the economic conditions and needs of accelerating Indonesia's energy transition. These economic findings suggest that policymakers should prioritize Li-Ion-based hybrid systems in future renewable energy planning, particularly in regions with existing hydropower infrastructure.

The 94.5% decarbonization achieved by Sce8, equivalent to mitigation of ~4.1 million kg CO_2/year compared to the Sce0 baseline, represented an important contribution to Indonesia's commitments under the Paris agreement and the 2060 net zero emission target. This level of emission reduction far exceeded Indonesia's NDC target of 43.2% by 2030, demonstrating that hybrid energy systems with high renewable energy penetration and battery storage were feasible and capable of delivering significant decarbonization outcomes. This achievement was accomplished while maintaining economic competitiveness, suggesting that the trade-off between decarbonization and economic viability often cited as a barrier to energy transition can be effectively managed through optimized hybrid system design. These results establish Sce8 as a replicable model for decarbonization in other regions with similar local characteristics and renewable resources.

If Sce8 were adopted and scaled up to other provinces with similar renewable resource potential, the aggregate decarbonization impact could substantially accelerate Indonesia's energy transition toward net zero emission. However, this study had several limitations that needed to be recognized: (i) it focused on a single type of storage for each configuration, while hybrid storage systems may offer different performance; and (ii) this simulation was based on thirty years of historical climate data that did not capture deeper climate change, considering that there was a possibility of climate change in air temperature based on the Mann-Kendall test results. Future research should explore the techno-economic aspects of hybrid storage technology, grid integration challenges, and climate change impact assessment on renewable resources. These efforts will be crucial to provide more comprehensive guidance for Indonesia's long-term energy transition planning.

4. CONCLUSION

This study optimized thirteen hybrid energy system configurations combining coal, hydro, FPV, and storage technologies (Li-Ion and PHS) to evaluate their techno-economic and climate-environmental performance in Indonesia, using ERA5 climate data and HOMER Pro optimization framework. Among the evaluated scenarios, Sce8 (coal-hydro-FPV-Li-Ion) emerged as the optimal configuration, achieving 91.1% renewable energy penetration, 94.5% decarbonization, and mitigation of ~4.1 million kg CO_2/year compared to the coal-based baseline. Economically, Sce8 produced a competitive LCOE of $0.1201/kWh, IRR of 7.6%, ROI of 5.9%, and a simple payback period of 8.7 years outperforming the PHS alternative (Sce12) with 38% lower CAPEX and 49% faster payback. These findings confirm that hybrid FPV-Hydro systems with Li-Ion battery storage represent a technically feasible, economically competitive, and climatically impactful pathway to reduce Indonesia’s dependence on coal-based power generation.

The decarbonization achieved by Sce8 significantly exceeded Indonesia’s NDC target of 43.2% by 2030, demonstrating that the optimization of hybrid energy systems can significantly contribute to Indonesia’s commitments under the Paris agreement and its net-zero emissions target by 2060. The approach applied in this study provided an adaptable and replicable model for hybrid renewable energy planning in regions with hydropower infrastructure and significant solar potential. Future research should focus on the challenges of grid integration, hybrid storage configurations, and the impact of climate change on the availability of renewable resources to strengthen the foundation of Indonesia’s long-term energy transition.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Firsta Zukhrufiana Setiawati	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Tania June	✓	✓		✓	✓	✓			✓	✓	✓	✓	✓	
Muh Taufik	✓	✓		✓	✓	✓				✓	✓	✓		
Rudi Kurnianto	✓	✓		✓	✓	✓			✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data generated and analyzed during this study are available with the permission of the corresponding author [initials, TJ] upon reasonable request for academic purposes.

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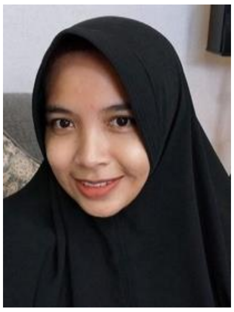
BIOGRAPHIES OF AUTHORS



Firsta Zukhrufiana Setiawati is currently a Doctoral Candidate in the Department of Geophysics and Meteorology, IPB University, Bogor, Indonesia; obtained her Master of Electrical Engineering (M.T.) from the Department of Electrical Engineering, Tanjungpura University, Indonesia; Bachelor's degree in Climatology from the College of Meteorology, Climatology and Geophysics, Indonesia; and Diploma in Meteorology from the Academy of Meteorology and Geophysics, Indonesia. She serves as a Junior Climatologist at the Indonesian Agency for Meteorology, Climatology, and Geophysics. Her research interests encompass applied climatology and renewable energy. She can be contacted at email: firsta.setiawati@bmkg.go.id, firstabmkg@gmail.com.

Tania June is currently Professor in Geophysics and Meteorology and Head of the Doctoral Program in Applied Climatology at IPB University and a senior researcher at the Collaborative Research Centre (CRC) 990 hosted by the University of Göttingen, Germany. She obtained her Doctor of Philosophy (Ph.D.) in Plant Sciences from the Environmental Biology Unit, RSBS-Australian National University, Australia; Master of Science (M.Sc.) in Tropical Crop Sciences from the University of Queensland, Australia; and Bachelor's in Agrometeorology from IPB University, Bogor, Indonesia. Her research interests encompass biogeophysics and biogeochemistry responses, micrometeorology, dynamics of heat/CO_2/H_2O fluxes, atmospheric characterization and precipitation formation processes. She can be contacted at email: taniajune@apps.ipb.ac.id.

Muh Taufik obtained his Ph.D. from Wageningen University (Netherlands), in 2017. He is currently Professor at the Department of Geophysics and Meteorology, IPB University, Bogor, Indonesia, specializing in Hydroclimatology, data analysis and visualization, and ecoHydrology. He also serves as Head of the Instrumentation and Environmental Modelling Laboratory at Centre of Environmental Research IPB. His research combines atmospheric, landscape, and Hydrological modelling with field data and remote sensing satellite imagery. He can be contacted at email: mtaufik@apps.ipb.ac.id.

Rudi Kurnianto is currently Professor and Head of the Master of Electrical Engineering Study Programme at the Faculty of Engineering, Tanjungpura University, Indonesia. He obtained his Doctor of Engineering (Dr. Eng.) at Toyohashi University of Technology, Japan; Master of Electrical Engineering (M.T.) at Bandung Institute of Technology (ITB), Indonesia; and Bachelor of Engineering (S.T) at Tanjungpura University, Indonesia. His expertise is in high voltage engineering, with research interests in electric power engineering and high field phenomena in dielectric materials. He can be contacted at email: rudi.kurnianto@ee.untan.ac.id.