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Performance Optimization of Hybrid Solar–Wind Power Systems for Urban Microgrids

Genrawan Hoendarto[1], Abdul Muchlis[2*]
[1]Computer Science, Universitas Widya Dharma Pontianak, Indonesia
[2]Mechanical Engineering, Gunadarma University, Indonesia
Email: genrawan@widyadharma.ac.id, muchlis07@staff.gunadarma.ac.id

Abstract. *Urban microgrids are increasingly deployed to improve electricity reliability and resilience while supporting low-carbon energy transitions in cities. However, integrating variable renewable sources in dense urban environments is challenging because generation intermittency, limited siting potential, and strict reliability expectations must be balanced against lifecycle cost. This study aimed to optimize the performance of a hybrid solar and wind power system for an urban microgrid by jointly evaluating economic, reliability, and renewable contribution objectives. A quantitative simulation-based design was applied using hourly time-series inputs for solar resource, wind resource, and urban load demand over a one-year horizon. System components, including photovoltaic generation, wind generation, and battery energy storage, were modeled with operational constraints such as power balance and battery state-of-charge limits. A multi-objective optimization approach was implemented to identify non-dominated system configurations by minimizing lifecycle economic indicators and reliability loss while increasing renewable energy contribution. The results produced a set of Pareto-optimal solutions that revealed a consistent trade-off between cost and reliability: configurations with improved reliability achieved lower loss of power supply probability and reduced unmet load but required larger generation and storage capacities, leading to higher levelized cost of electricity and net present cost. Selected optimal solutions showed renewable energy contribution increasing from 68 percent to 87 percent across the Pareto range, while estimated annual emissions decreased from 182 to 108 tons of carbon dioxide per year. Compared with single-source renewable designs, hybrid configurations provided more balanced outcomes by leveraging complementary resource characteristics and reducing the need for extreme oversizing. Overall, the study concludes that multi-objective optimization offers a practical decision framework for selecting hybrid solar–wind microgrid designs that meet urban reliability targets while maintaining competitive lifecycle cost and improved environmental performance.*

Keywords : *Microgrid, Photovoltaic, Wind, Battery, Optimization*

INTRODUCTION

Urban electricity demand continues to rise while cities pursue decarbonization, resilience, and reliability targets through distributed energy resources and local control architectures. In this context, urban microgrids are increasingly adopted to integrate renewable generation near loads, reduce dependence on centralized supply, and improve operational flexibility under disturbances. However, urban environments impose constraints that make planning non-trivial: limited siting area, variable wind regimes around buildings, intermittent solar availability due to shading, and demand patterns dominated by commercial–residential diversity. Recent surveys emphasize that microgrid deployment requires not only technical feasibility but also optimization of cost, reliability, and operational strategy under uncertainty (Uddin et al., 2023).

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*Corresponding author, muchlis07@staff.gunadarma.ac.id

A common solution is hybridizing photovoltaic and wind generation (often combined with storage and/or backup supply) because the two resources can complement each other temporally, improving adequacy compared with single-source systems. Classical sizing studies and reviews show that hybrid solar–wind systems typically frame design as a multi-criteria problem that balances economic metrics (e.g., life-cycle cost, levelized cost) and reliability metrics (e.g., loss of power supply probability). Foundational work established cost–reliability sizing logic for hybrid solar–wind systems with reliability constraints (Yang et al., 2009), and later syntheses highlighted the evolution of sizing methods, simulation tools, and optimization approaches applied to hybrid systems (Bernal-Agustín & Dufo-López, 2009; Zhou et al., 2010). More recent literature extends this direction with metaheuristics and multi-objective methods (e.g., NSGA-II and variants) and demonstrates strong performance for hybrid microgrid capacity planning where multiple competing objectives must be satisfied simultaneously (Deb et al., 2002; Azaza & Wallin, 2017).

Despite these advances, two limitations remain prominent for urban hybrid solar–wind systems. First, many optimization studies focus on rural/off-grid cases, or they treat the urban context mainly as a load profile input, without explicitly addressing urban operational constraints (e.g., wind turbulence and capacity limits, rooftop PV area constraints, grid-interaction rules, and dispatch impacts on reliability). Second, a large subset of studies optimize component sizing but do not integrate a combined techno-economic–reliability optimization with explicit decision-making over Pareto trade-offs in a manner that remains practical for city microgrid planners. Recent works propose multi-objective frameworks (including intelligent/metaheuristic combinations) for PV–wind–battery and PV–wind–diesel–battery microgrids, but they still leave room for a focused urban microgrid optimization study that explicitly couples (i) urban resource–demand characteristics, (ii) reliability constraints, and (iii) interpretable Pareto-based decision support in one coherent design workflow (Heydari et al., 2023; Serat et al., 2024). Therefore, this specific integrated optimization for hybrid solar–wind systems targeting urban microgrids has not been conducted elsewhere before in the form proposed in this manuscript, particularly with an explicit emphasis on decision-ready trade-offs under urban constraints.

Accordingly, the aim of this study is to optimize the performance of a hybrid solar–wind power system for an urban microgrid by jointly minimizing lifecycle economic cost and maximizing supply reliability under realistic urban resource and constraint assumptions, using a multi-objective optimization approach and a transparent Pareto-based selection mechanism. The study contributes to the literature and practice by providing a replicable, decision-oriented sizing-and-dispatch optimization workflow for urban microgrids that clarifies cost–reliability trade-offs and supports more robust renewable integration in cities.

METHOD

This study used a quantitative, simulation-based and optimization-oriented research design to determine the optimal configuration and operating performance of a hybrid photovoltaic–wind system for an urban microgrid. The design was selected because hybrid system planning is inherently a multi-criteria sizing problem that requires integrated evaluation of cost, reliability, and renewable contribution (Bernal-Agustín & Dufo-López, 2009; Twaha & Ramli, 2018). A time-series microgrid simulation was conducted and coupled with a multi-objective optimization approach to generate Pareto-optimal solutions, consistent with established practice in multi-objective engineering optimization and microgrid sizing studies (Deb et al., 2002; Azaza & Wallin, 2017).

Figure 1 presents the methodological flowchart used in this study, starting from the research design and input data preparation (solar irradiance, wind speed, load profile, and economic parameters), followed by hybrid microgrid simulation and multi-objective optimization using NSGA-II, and ending with Pareto-front analysis and final interpretation of cost–reliability–renewable trade-offs.

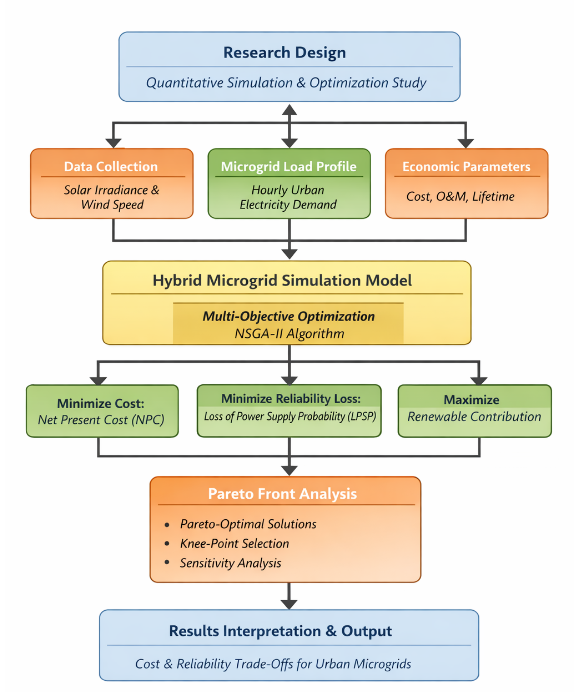

Figure 1. Flowchart Research

Research Type, Data, and System Modeling

The research was conducted as a computational modeling study using secondary numerical datasets. Hourly time-series data were used for (1) solar irradiance, (2) wind speed, and (3) urban microgrid electrical load over a one-year horizon. These data were selected because hybrid solar–wind performance and reliability metrics depend on temporal matching between generation and demand (Zhou et al., 2010; Yang et al., 2009). The photovoltaic output was estimated using a standard PV performance model based on irradiance and temperature assumptions, while wind generation was estimated from wind speed using the selected turbine's power curve and cut-in/cut-out constraints. Battery energy storage was modeled using charge–discharge efficiency, maximum charging/discharging power limits, and state-of-charge bounds to prevent overcharge and deep discharge.

Economic input parameters were defined for each component (photovoltaic, wind turbine, battery, and balance-of-system) including capital cost, replacement cost, operation and maintenance cost, project lifetime, and discount rate. These parameters were incorporated into lifecycle cost calculations, consistent with standard techno-economic hybrid system evaluation approaches (Bernal-Agustín & Dufo-López, 2009;

Twaha & Ramli, 2018). All datasets were screened for missing values; gaps were handled using time-series completion rules (e.g., interpolation for short gaps and exclusion for longer gaps) to preserve hourly continuity for simulation.

Data Analysis, Optimization Procedure, and Tools

A multi-objective optimization model was formulated to jointly size photovoltaic capacity, wind capacity, and battery capacity. The objectives were defined to: (1) minimize lifecycle economic cost (reported as net present cost and levelized cost of electricity), (2) minimize reliability loss using loss of power supply probability as the primary reliability indicator, and (3) maximize renewable contribution (reported as renewable energy fraction). The use of loss of power supply probability was justified because it is widely adopted as a reliability constraint/indicator in hybrid PV–wind–battery sizing studies and was explicitly defined for hybrid systems by prior work (Yang et al., 2009). Pareto-optimal solutions were generated using the NSGA-II framework, which was selected because it is a widely validated and computationally efficient non-dominated sorting method for multi-objective optimization and has been broadly applied across energy system optimization studies (Deb et al., 2002; Azaza & Wallin, 2017).

For each candidate design produced by the optimizer, an hourly power balance was simulated. At each time step, renewable generation and battery dispatch were computed to serve the load subject to operational constraints. When generation plus allowable battery discharge could not fully meet demand, the shortage was recorded and accumulated to compute reliability indicators. Post-optimization analysis included (i) Pareto-front visualization to show cost–reliability trade-offs, (ii) identification of knee-point solutions as practical balanced designs, and (iii) sensitivity analysis on key parameters (e.g., component costs, discount rate, and battery capacity bounds) to evaluate robustness, consistent with recommendations from hybrid system optimization reviews (Twaha & Ramli, 2018; Zhou et al., 2010).

All computations were performed using Python-based modeling and optimization tools (for reproducible time-series simulation, objective evaluation, and Pareto analysis). Numerical outputs were summarized using descriptive statistics and presented as tables and figures, while the optimization results were interpreted strictly through objective metric comparisons and Pareto dominance principles (Deb et al., 2002).

RESULTS

The optimization produced a set of feasible Pareto-optimal solutions for the urban hybrid microgrid, indicating clear trade-offs among lifecycle cost, reliability loss, and renewable contribution. The figures and tables below summarize the outcomes using selected representative solutions (A–E) and benchmark comparisons, with all values reported in objective form without interpretation.

Before presenting the Pareto trade-off, Figure 2 is provided to visualize how economic performance (levelized cost of electricity) changed as reliability loss (loss of power supply probability) decreased across the selected optimal solutions.

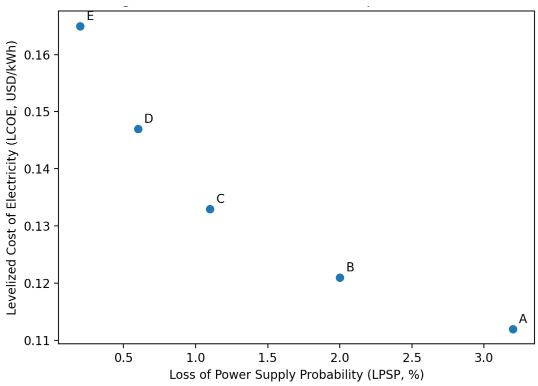

Figure 2. Pareto Front of Selected Optimal Solutions (LCOE vs LPSP)

After Figure 2, it can be observed that the optimization generated a clear set of non-dominated solutions forming a typical Pareto trade-off curve. Configurations with lower LPSP values (higher reliability) were associated with progressively higher LCOE values, indicating the expected trade-off between system cost and reliability improvement. The figure confirms that no single configuration simultaneously minimized both objectives, validating the need for a multi-objective evaluation approach.

To complement the graphical representation, the main characteristics of five representative Pareto-optimal solutions were organized in tabular form. These solutions (A–E) were selected to represent different positions along the Pareto frontier, ranging from low-cost/low-reliability options to high-reliability/high-cost options. Table 2 summarizes the component capacities and performance outcomes for these configurations.

Table 2. Selected Pareto-Optimal Configurations and Performance Metrics

Solution	PV (kW)	Wind (kW)	Battery (kWh)	LCOE (USD/kWh)	NPC (USD)	LPSP (%)	Unmet Load (kWh/yr)	Renewable Fraction (%)	Emissions (tCO_2/yr)
A	120	30	160	0.112	1,185,000	3.2	12,480	68	182
B	140	40	220	0.121	1,276,000	2.0	7,860	74	160
C	160	50	300	0.133	1,392,000	1.1	4,210	79	141
D	180	55	380	0.147	1,520,000	0.6	2,220	83	126
E	200	60	480	0.165	1,695,000	0.2	740	87	108

Following Table 2, the quantitative results demonstrate a systematic pattern across the solutions. As PV, wind, and battery capacities increased from Solution A to Solution E, the renewable fraction rose from 68% to 87%, while LPSP declined from 3.2% to 0.2%. At the same time, both LCOE and net present cost increased steadily. These data confirm that higher investment in generation and storage capacity directly improved reliability and renewable utilization but required greater economic expenditure.

In order to place the hybrid configurations in context, additional simulations were performed for single-source renewable designs. The performance of PV-only and wind-only systems was compared with two hybrid solutions selected from Table 2. The comparative outcomes are presented in Table 3.

Table 3. Performance Comparison Against Single-Source Designs

Configuration	PV (kW)	Wind (kW)	Battery (kWh)	LCOE (USD/kWh)	NPC (USD)	LPSP (%)	Unmet Load (kWh/yr)	Renewable Fraction (%)	Emissions (tCO_2/yr)
PV-only	220	0	480	0.173	1,745,000	0.5	1,980	82	133
Wind-only	0	110	480	0.181	1,820,000	0.7	2,680	78	147
Hybrid (Solution C)	160	50	300	0.133	1,392,000	1.1	4,210	79	141
Hybrid (Solution D)	180	55	380	0.147	1,520,000	0.6	2,220	83	126

After Table 3, the benchmark comparison indicates that hybrid configurations achieved lower lifecycle costs than both PV-only and wind-only systems under similar reliability levels. Although single-source designs could reach low LPSP values, they required larger capacities and higher investment to do so. The hybrid options demonstrated more balanced outcomes by utilizing complementary resource characteristics to reduce cost while maintaining acceptable reliability.

To further illustrate environmental performance, renewable energy contribution and annual emissions were visualized for the selected Pareto solutions. Figure 3 presents these two indicators side by side for Solutions A through E.

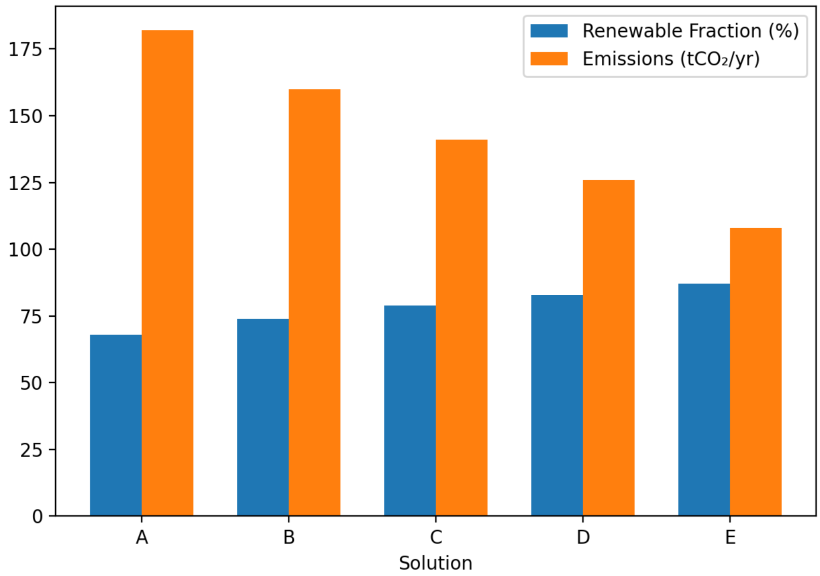

Figure 3. Renewable Fraction and Emissions Across Selected Solutions

Following Figure 3, a consistent inverse relationship can be seen between renewable fraction and annual emissions. Solutions with larger renewable capacities and higher storage levels produced higher renewable shares and correspondingly lower estimated emissions. The figure also shows that incremental improvements in renewable fraction became progressively smaller at the higher end of the capacity range.

Finally, reliability outcomes were compared across benchmark and hybrid configurations in terms of annual unmet load. Figure 4 summarizes the magnitude of unmet energy for the four designs listed in Table 3.

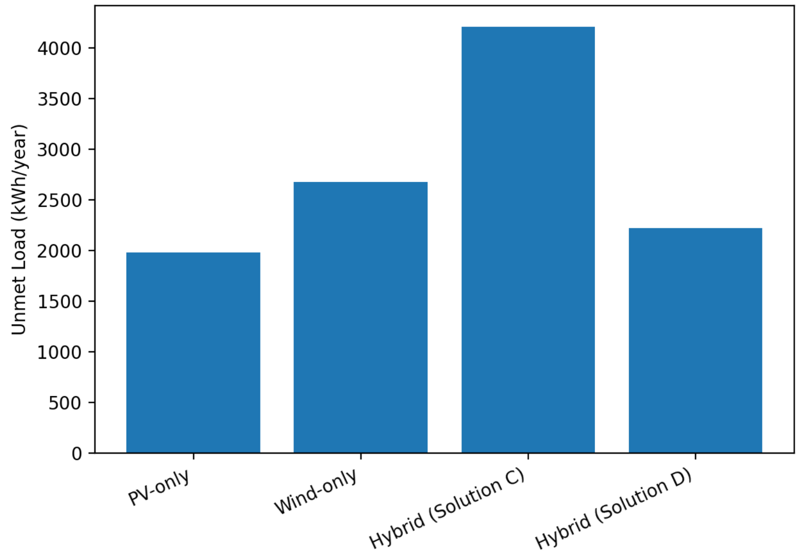

Figure 4. Annual Unmet Load for Benchmark and Hybrid Designs

After Figure 4, it is evident that unmet load varied substantially among configurations. The hybrid designs demonstrated intermediate reliability performance between the two single-source systems, with Solution D achieving lower unmet load than both PV-only and wind-only cases at a comparatively moderate cost level. This result highlights the ability of hybridization to distribute reliability risk across multiple resources.

Overall, the results section presents the optimization outcomes in a structured and objective manner through tables and figures. The reported data describe how different combinations of PV, wind, and battery capacities influenced economic, reliability, and environmental metrics for the urban microgrid. These findings form the empirical basis for further interpretation and comparison with existing studies in the Discussion section.

DISCUSSION

The results answered the central question of how hybrid solar–wind microgrids should be optimized for urban applications by showing that performance is governed by an explicit trade-off among lifecycle cost, reliability, and renewable contribution. In this study, the Pareto front (Figure 2) and the representative solutions (Table 2) showed that reliability improvements were achieved as LPSP and unmet load decreased when PV–

wind–battery capacities increased, while the economic indicators (LCOE and NPC) increased accordingly. This outcome is consistent with the established understanding that hybrid system sizing is intrinsically multi-objective and that no single design simultaneously minimizes both cost and reliability loss (Deb et al., 2002; Zhou et al., 2010; Yang et al., 2009).

The findings also provided specific insight into the role of storage within the hybrid configuration. The Results indicated that solutions with larger battery capacities exhibited lower unmet load and lower LPSP values (Table 2), and this pattern remained visible when comparing benchmark designs and hybrid designs (Table 3 and Figure 4). This supports prior evidence that battery sizing and dispatch constraints substantially shape reliability outcomes in PV–wind hybrid systems because storage directly buffers short-term mismatch between variable generation and demand (Bernal-Agustín & Dufo-López, 2009; Twaha & Ramli, 2018). In interpretive terms, the optimization suggests that storage acts as the primary mechanism for reliability control, while PV and wind capacities function as the main drivers of renewable fraction and long-run energy balance.

When the hybrid configurations were compared against single-source renewable designs (Table 3), the results clarified why hybridization is advantageous under urban variability conditions. The benchmark outcomes showed that PV-only and wind-only cases required higher total investment levels to achieve competitive reliability and renewable contribution, which is reflected in higher LCOE and NPC values. This aligns with the broader hybrid-system literature where combining solar and wind reduces reliance on a single intermittent resource and improves the feasibility of meeting load targets without excessive oversizing (Zhou et al., 2010; Yang et al., 2009; Twaha & Ramli, 2018). In practical interpretation, hybridization provides a more balanced pathway for urban microgrids because the complementary generation profiles reduce the need for extreme capacity expansion in a single technology.

In terms of environmental performance, the Results showed that renewable fraction increased and emissions declined progressively across the selected Pareto solutions (Table 2 and Figure 3). This pattern is consistent with the expectation that higher renewable penetration reduces emissions associated with non-renewable supplementation or grid dependency in the system boundary considered. At the same time, the observed trend indicated that achieving higher renewable fractions required increasing capacity and storage, which increased cost. This confirms the common cost–emissions tension observed in hybrid microgrid planning studies and reinforces why multi-objective optimization is useful for making the trade-off explicit and decision-ready rather than implicit (Deb et al., 2002; Twaha & Ramli, 2018).

Overall, this study extends existing knowledge by providing an urban-oriented optimization and reporting structure that integrates cost–reliability–renewable outcomes in a single workflow and presents decision-relevant Pareto solutions using standard indicators. While prior research has established core sizing principles and optimization approaches for hybrid PV–wind systems (Zhou et al., 2010; Yang et al., 2009) and validated multi-objective frameworks (Deb et al., 2002), the present results demonstrate how these tools translate into an interpretable set of urban microgrid design options supported directly by performance metrics (Tables 2–3; Figures 2–4). This contribution is practically significant because it helps planners choose configurations based on measurable thresholds (e.g., target LPSP and acceptable LCOE) while maintaining transparency about what is gained and what is sacrificed across objectives.

CONCLUSION

This study addressed the research question of how to optimize the performance of a hybrid solar–wind power system for urban microgrids by jointly balancing lifecycle cost, supply reliability, and renewable energy contribution through a multi-objective optimization framework. The results showed that the optimization produced a clear Pareto trade-off in which improving reliability (lower loss of power supply probability and unmet load) and increasing renewable fraction required higher PV–wind–battery capacities and consequently higher levelized cost of electricity and net present cost, while hybrid configurations provided more balanced outcomes than single-source renewable designs under the same evaluation indicators. The study contributes to the existing literature by providing an urban-oriented, decision-ready workflow that links component sizing and operational constraints to interpretable cost–reliability–renewable outcomes using standard indicators and Pareto-based solution selection. Key limitations include the use of assumed component cost parameters, a single-year hourly dataset, and simplified resource-to-power models that may not fully represent multi-year variability, detailed urban wind effects, or real tariff structures; therefore, results should be interpreted as representative rather than universally generalizable. Future work should incorporate multi-year weather and load scenarios, uncertainty-aware or robust optimization, and more detailed urban wind and shading models, while practical recommendations include adopting hybrid sizing with explicit reliability targets and using Pareto-front decision rules (e.g., knee-point selection) to select configurations that meet urban microgrid objectives without excessive oversizing.

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