

Research article

Grid–variable renewable energy supply optimization for sustainable tourism in developing countries: A case of small-sized hotels in low-wind regions

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Abstract: This study assesses the techno-economic viability of grid-connected variable renewable energy (VRE) systems for small-sized hotels in low-wind areas of developing tropical countries where the sustainable tourism infrastructure is subjected to unique resource constraints. This paper compares three optimization methods—linear programming (LP), simulated annealing (SA), and the genetic algorithm (GA)—to determine the optimal levelized cost of energy (LCOE), component sizing, and generation mixes across four regulatory scenarios, using the hourly load and resource profiles of a planned hotel on Nusa Penida Island, Bali, Indonesia. Methodological comparison of these techniques unveils distinct computational trade-offs, with LP providing the fastest optimization (54.35 to 162.16 s), drastically outperforming iterative metaheuristics such as GA, which required up to 772.18 s. Regarding energy performance, all photovoltaic (PV)-integrated configurations outperform the grid-only benchmark of \$0.0824/kWh. The PV–grid system yields the lowest LCOE (\$0.0637 to \$0.0714/kWh), reducing costs by 3.2% to 15% compared with the grid. Notably, hybrid wind–PV–grid configurations are economically feasible (\$0.0662 to \$0.0798/kWh), successfully meeting demands even under a stringent 25% obligatory renewable fraction. Without sellback incentives, the VRE mix ranges from 30.1% to 38.2% for PV–grid systems and reaches up to 49% for wind–solar–grid setups, whereas elevated sellback rates strongly boost VRE adoption. This study has practical implications for policymakers and hospitality investors by showing that while solar PV remains the most cost-effective asset, small wind turbines can synergistically complement grid–VRE systems in low-wind tropical environments when supported by strategic market mechanisms.

Keywords: grid-connected variable renewable energy; sustainable tourism infrastructure; low-wind regions of developing tropical countries; linear programming; simulated annealing; genetic algorithm; techno-economic; hourly load and resources profiles

1. Introduction

Sustainable tourism is gaining recognition as one of the pathways for developing countries to enhance economic growth while safeguarding the environment and promoting public health [1,2]. The hospitality sector consumes a significant amount of electricity for lighting, temperature regulation, hot water, and various other services for guests [3]. It is a significant contributor to greenhouse gas emissions and exerts pressure on the local ecosystem [4]. Hotels and similar businesses must transition to cleaner, more reliable, and affordable energy sources to combat climate change, reduce expenses, and enhance their preparedness for energy supply issues and fluctuations in fossil fuel prices [5,6]. The costs associated with variable renewable energy (VRE) technologies, particularly solar photovoltaic (PV) and wind energy, have decreased significantly over the past decade. This has made them more accessible even in areas with scarce resources, while current challenges include overproduction in some places [7,8]. Innovative policies and funding strategies, such as subsidies, feed-in tariffs, renewable energy certificates, concessional loans, and blended finance approaches, have supported developing countries in embracing VRE by reducing the investment risks and initial costs [9]. Despite challenges such as an unreliable grid infrastructure, intermittent resources, and regulatory ambiguities, developing countries are presently well positioned to utilize decreasing costs and enhanced institutional frameworks to adopt VRE in the tourism industries.

The challenges of using wind energy in areas with low-wind regimes may be addressed by modifying the turbine and blade design [10]. Research indicates that enhancing the design of wind turbines, including small wind turbines, significantly improves their performance in low-wind conditions [11,12]. Hybridization of the energy supply, e.g., integrating solar PV with wind, storage, or grid backup, may also be another way to adopt VRE. It can help with variability, increase the proportion of renewable energy, and reduce the levelized cost of energy (LCOE) [13]. This implies that hotels, even smaller ones, can consider implementing on-site hybrid on-grid or off-grid renewable energy setups that benefit the environment, reduce costs, and boost branding in sustainable tourism sectors.

Limited research has examined the design and enhancement of hybrid VRE systems in hotels or comparable hospitality venues, focusing on cost, emission reduction, or reliability improvements. A study utilized 10-year wind speed data to explore the potential of small wind turbines for small hotels in three different Indonesian sites with diverse wind speed patterns [14]. By using Seasonal Autoregressive Integrated Moving Average (SARIMA) and the Holt–Winters forecasting models, the authors found that a 30-kW turbine could meet between 8% and 35% of the hotel’s electricity needs, depending on occupancy levels. Other research utilized a metaheuristic algorithm named quadratic interpolation beluga whale optimization (QIBWO) to optimize a hybrid microgrid for a small hotel, incorporating solar PV, wind, battery storage, and electric vehicle charging stations [15]. The research reached a renewable energy share of roughly 96% with an LCOE of about US\$ 0.0533/kWh.

A solar–wind–battery system operating off the grid for a tourism village in Bahuluang, Indonesia, was developed and optimized utilizing the Hybrid Optimization of Multiple Electric Renewables (HOMER) software [16]. With a 172-kW solar PV system and a 36-kW wind turbine

capacity, in addition to energy storage batteries, the authors discovered that wind contributes roughly 82% to the energy generation mix, while solar only accounts for about 17%. A different study showcased an optimization assessment of a hotel's grid-tied hybrid renewable energy system considering technical, economic, and environmental aspects [17]. The suggested system includes solar, wind, and biogas generators, leading to a net present cost of \$388,000, which is considerably less than the electricity grid's cost of \$873,000. Researchers in Thailand explored how solar PV and its system design factors could minimize the carbon footprint of small hotels [18]. The researchers found that the building's orientation, angle of tilt, and the direction of solar panel placement all influenced the best reduction in the carbon footprint. A recent study evaluated the effects of solar PV–battery systems on energy use and expenses in homestay hotels, accounting for varying occupancy rates and reservation prices [19]. The researchers discovered that renewable energy production can boost a hotel's earnings based on occupancy levels and booking rates. A previous study examined the ideal design of hybrid PV–wind–battery–diesel systems for a combined building that includes a hotel, in both on-grid and off-grid scenarios [20]. Using a nonlinear swarm optimization algorithm to reduce costs and enhance the renewable fraction, the author discovered that on-grid setups are more economical, while a rapid rise in demand necessitates significant energy storage capacity, leading to increased energy costs.

Aside from the literature on the potential role of VRE in the hospitality industry, current research aims to improve the accuracy of solar radiation and predicted energy generation under local climate conditions to help the system operator achieve better operational efficiency. An important study in Saudi Arabia compared different artificial intelligence (AI) models, especially for the prediction of global horizontal irradiance (GHI), where deep learning architectures were compared with RMSprop optimization [21]. Furthermore, a power generation forecasting study has proposed a hybrid AI model that integrates a random vector functional link (RVFL) network and the Eurasian lynx optimization algorithm (ELOA) to mitigate the uncertainty of solar energy [22]. The model has been tested on a 1.50-GW solar project for a period of 1 year and shows potential for enhancing smart grids' stability across seasonal variations.

In another study, a hybrid long short-term memory (LSTM) model optimized using the brown bear optimization algorithm was applied to forecast the photovoltaic performance of floating and ground-mounted solar systems in difficult environmental conditions [23]. A recent review study emphasized the significance of AI, energy storage technologies, and stochastic optimization algorithms in enhancing microgrids' efficiency and reliability, particularly in managing the variability of renewable energy. While machine learning offers potential improvements in operational stability, the study identified challenges related to technology integration, simulation accuracy, and the sustainability of energy storage [24].

From the aforementioned literature review, three research gaps are evident: (1) A scarcity of research specifically addressing small hotels in low-wind tropical developing countries, (2) a lack of direct comparisons between deterministic and stochastic/global optimization algorithms for hybrid grid–VRE sizing in hotel contexts, and (3) an absence of joint optimization that simultaneously presents LCOE, the renewable generation mix (percentage of PV, wind, or grid), and the optimal quantity of physical units (e.g., discrete counts of identical small wind turbines or PV arrays) based on hourly demand data and VRE resources in tropical climates, as well as the impact of the VRE fraction and economic regulations such as electricity sellback tariffs on systems' LCOE.

This study aims to address these gaps by conducting a techno-economic analysis of hybrid grid–PV–wind systems for small-sized hotels in developing tropical countries with low wind speeds.

This study uses three optimization techniques, namely linear programming (LP) for baseline deterministic sizing, simulated annealing (SA) as a typical local search metaheuristic, and the genetic algorithm (GA) as a global evolutionary optimizer, to assess the potential system setups, including their LCOE, renewable generation mix, and the number of units of each technology involved. The simulation models hourly temporal data for electricity demand and VRE supply resources, while accounting for economic regulations on the sellback tariff and the required VRE fraction.

While the study does not emphasize introducing new optimization algorithms, the contributions of this study include the following. First, it offers a methodological comparison of LP, SA, and GA for hybrid grid–VRE systems in small hotels operating under low-wind tropical conditions. Second, it showcases algorithmic trade-offs in the solutions' quality and computational efficiency. Third, it measures the possible techno-economic outcomes (LCOE, renewable contributions, component quantities) for small hotels based on realistic hourly resource and load profiles. Further motivation for this study includes informing hotel operators, investors, and policymakers on sustainable energy transition methods for the tourism industry, especially for small accommodation providers in low-wind areas, thus aiding sustainable tourism, energy accessibility, cost savings, and environmental objectives. It emphasizes practical guidance on the cost-effectiveness of small wind turbines (in hybrid setups with PV and the grid) in low-wind tropical environments, the synergies between PV and wind, and the influence of grid pricing on the sustainable energy transition in the tourism industry.

The remainder of this paper is arranged as follows. Section 2 describes the methods used in this paper, including input data, modeling assumptions, and optimization techniques. Section 3 contains the results, while Section 4 provides a discussion. Finally, Section 5 provides the paper's conclusions.

2. Methods

This section discusses and elaborates on some important aspects involved in the analysis. These are the chosen geographical location of the planned small hotel, an evaluation of the electricity needs of the hotel, the optimization methods used and the problem's formulation, and the operational assumptions and simulation scenarios for the systems. This section also contains the techno-economic assumptions and resource dataset of the VRE technologies (i.e., solar PV and wind turbines (WTs)) studied in the research.

2.1. The hotel's location and electricity demand

For the case study, the hotel's geographical coordinates are -8.75 S, 115.48 E. It is located in one of the most famous tourist destinations, Nusa Penida Island, which is part of Indonesia's Bali Province. Bali is a tropical island located east of Java and west of Lombok. This study focuses on small hotels due to their significant electricity consumption for everyday operations. Although a small hotel's overall energy consumption may be less than that of a large hotel, its energy usage per square meter (energy intensity) can still be quite high [25,26]. Simultaneously, Nusa Penida Island has significant potential for the development of VRE, particularly solar energy. Wind energy, however, is still viewed as a complement to solar energy, given the tropical region's low wind speeds [14,27,28]. Figure 1 displays the map of Bali Island and Nusa Penida Island, located to the southeast of Bali Island. The red spot on Nusa Penida Island marks the small hotel's position. The map is taken from <https://power.larc.nasa.gov/data-access-viewer/>.

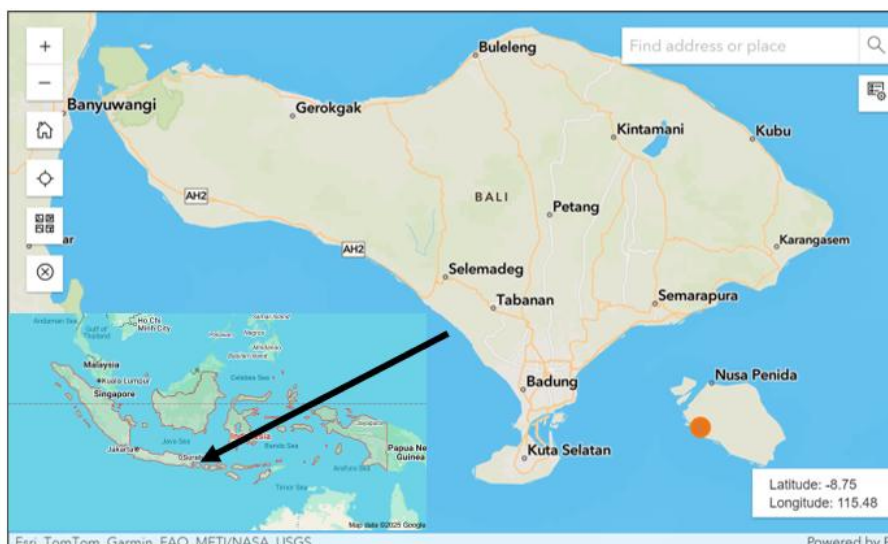


Figure 1. A map showing the hotel's location, marked with a red spot, on Nusa Penida Island, southeast of Bali Island.

This study determines the hotel's electricity demand for the case study by synthesizing available data on the hourly daily electricity demand of a comparable hotel [29] and applying the region's monthly occupancy rate and the reference occupancy rate to estimate the hourly daily electricity demand. This study calculates the hourly kWh demand by multiplying the available hourly kWh data [29] by the ratio of the monthly occupancy rate to the weekly occupancy rate for the reference hotel. The monthly occupancy rate of the hotel was obtained from BPS-Statistics Indonesia, Bali office [30]. Figure 2 illustrates the assumed hourly-based daily electricity demand of the small 21-room hotel utilized in this study. Saturday and Wednesday have the highest and the lowest daily energy usage of 252 kWh and 166 kWh, respectively. Figure 3 shows the pseudocode used for determining the hotel's occupancy.

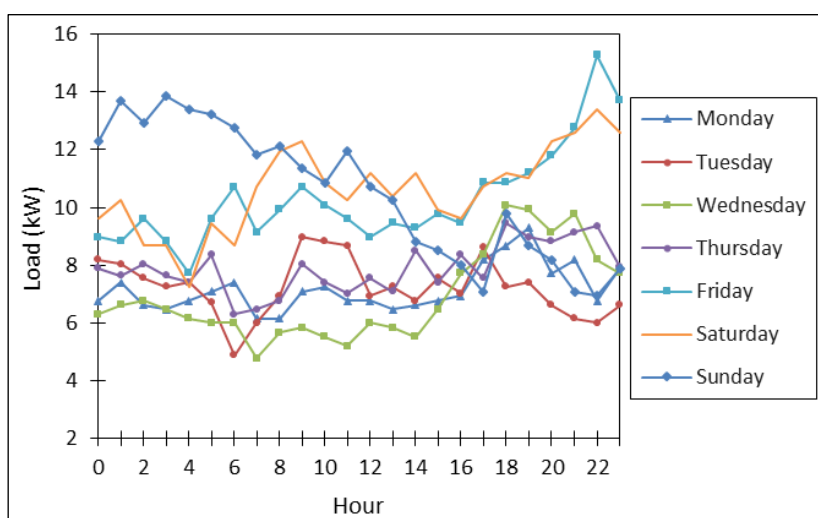


Figure 2. The determined hourly-based daily electricity demand of the small hotel.

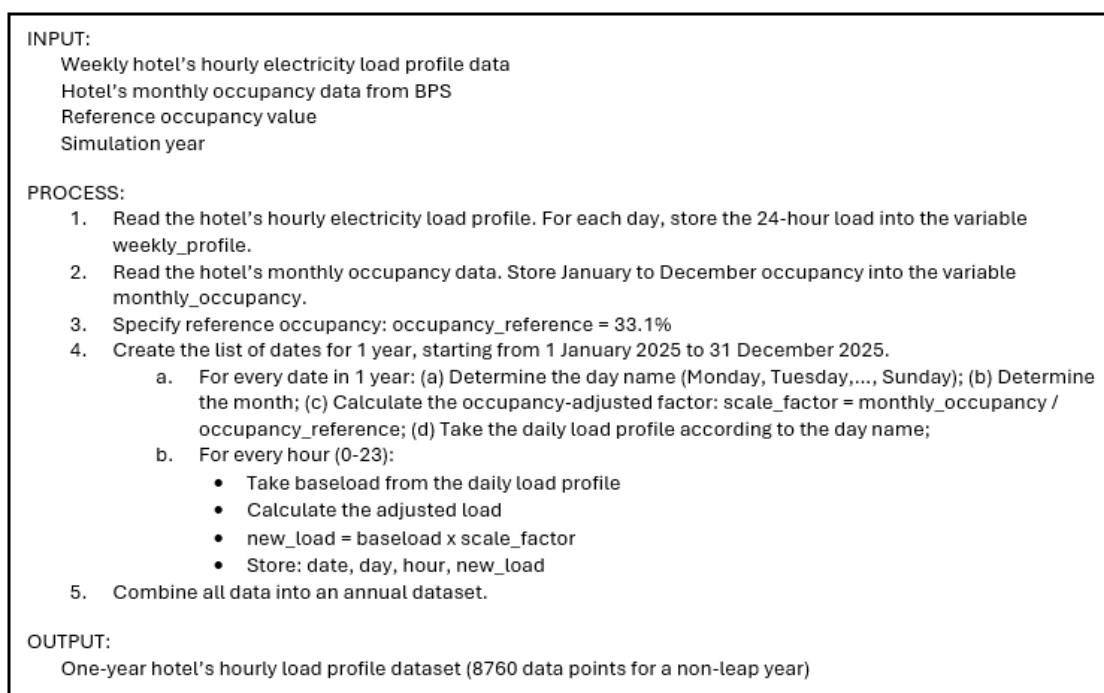


Figure 3. The pseudocode for determining the hotel's occupancy.

2.2. Optimization techniques and simulation scenarios

As stated in Section 1, this research uses three optimization methods, namely LP, SA, and the GA, to explore the potential grid–VRE system configurations for small hotels in tropical areas with low wind speeds. This study specifically compares these three optimization methods in terms of the LCOE, the fraction of renewable energy, the energy generation mix, and the quantity of units for the optimized grid–VRE system configurations, as well as the computational time required for the simulations.

Every optimization technique seeks to minimize the LCOE of the possible grid–VRE combinations (on-grid) while meeting the hourly electricity needs of the hotel, as detailed in Section 2.1. In this context, the simulation runs for a year (8760 hours), accounting for the annual potential energy produced by solar PV and wind, along with “standby” energy supplied by the grid. This research examines a system lifespan of 25 years to determine the LCOE for each grid–VRE configuration derived from the simulations. This study, therefore, does not model the role of energy storage, such as batteries, in supporting the VRE-based electricity supply.

In every hour of the simulation period, the algorithm assesses the energy produced by VRE against the hotel's consumption needs. The grid will supply electricity when the necessary demand cannot be fulfilled solely by VRE. The simulation identifies the count of PV and/or wind units that constitute the optimization outcome, taking into account the energy provided by VRE, which is converted from the hourly solar irradiation and wind speed data (outlined in Section 2.4). The possible units that can be involved in the optimization results are evaluated against resource availability at that particular hour. In this context, all optimization techniques also primarily consider the costs of each VRE technology, primarily focusing on capital cost, installation cost, and operation and maintenance cost (see Section 2.4) as part of the simulation process's considerations.

The simulation is constructed using Python by applying some of the libraries and modules provided in Python. These include Pandas (to read and process data in an Excel file for hourly wind

speed, solar irradiation, and electricity demand), Openpyxl (to read the resource data and convert them into electricity in Excel), Numpy (to process mathematical operations and arrays, such as conversion of wind speed into electricity, energy calculation, and data normalization), PuLP (to develop and solve LP models), Simanneal (to solve optimization problems with SA), Pygad (to solve optimization using the GA, i.e., to find optimal solutions from energy resource allocation based on a fitness function), Matplotlib (to visualize data, graphs, and other optimization results), and Time (to record the execution time of each optimization method).

This study does not account for any unmet energy needs. Because the hotel is assumed to remain connected to the utility in all scenarios and to have no energy storage, the grid's electricity supply is assumed to be completely reliable. The grid fills any gap between renewable generation and load demand, ensuring that hourly electricity demand is fully met throughout the simulation period in the absence of VRE supply. Unmet demand is not allowed in the optimization problem, as formulated by the energy balance constraint equations (see Eqs (3)–(13)), which involve electricity generated by PV and wind, electricity supplied to or exported to the grid, and curtailed electricity, across all scenarios.

This study examines four scenarios to obtain the optimization results of grid–VRE setups. These include Scenario 1 (no sellback), Scenario 2 (20% sellback rate), Scenario 3 (50% sellback rate), and Scenario 4 (25% renewable energy fraction). Scenario 1 demonstrates the existing electricity pricing structure for renewable energy use by residential customers in Indonesia or other countries that do not reimburse for electricity returned to the grid. Scenario 2 demonstrates a basic payment that consumers would receive for returning their surplus electricity to the grid. Scenario 3 demonstrates a noticeably greater remuneration that customers would earn by returning their surplus electricity to the grid. A 50% sellback rate is considered reasonable because a higher sellback rate (net metering) of 65% was once applied, for example, in Indonesia, for domestic on-grid PV installations.

These four scenarios are further classified into three conditions that correspond to the system's behavior, namely the “no sellback”, “with sellback”, and “renewable fraction” conditions. The first condition prohibits the export of electricity. Any renewable generation that exceeds the load's demand is curtailed and considered to be waste energy. The second condition allows excess renewable electricity to be exported to the grid. As a result, renewable surplus is treated as electricity sold back to the utility. Meanwhile, the “renewable fraction” condition seeks to achieve the lowest LCOE combination of PV and wind turbine capacities while meeting a predetermined renewable fraction target. No individual minimum contribution is required for PV or wind; only the total renewable contribution is limited. The optimization problem formulation, which includes the decision variables, objective function, and constraints used in the simulated systems, is provided below.

Decision variable (DV):

$$DV = N_{PV} \in Z \text{ and } N_{WT} \in Z \quad (1)$$

Objective function: Minimize the LCOE

$$Z = \sum_{t=1}^T (C_{PV,t} \times P_{PV,t} + C_{WT,t} \times P_{WT,t} + C_{Grid,t} \times P_{Grid,t}) \quad (2)$$

Constraints:

$$P_{Grid,t} \geq 0; P_{PV,t} + P_{WT,t} + P_{Grid,t} \geq P_{Load,t} \quad (3)$$

No sellback

- Sellback constraint:

$$P_{Sell,t} = 0 \quad (4)$$

- Energy balance:

$$P_{PV,t} + P_{WT,t} + P_{Grid,t} = P_{Load,t} + P_{Curt,t} \quad (5)$$

- Curtailment: The surplus energy is discarded

$$If: P_{PV,t} + P_{WT,t} \geq P_{Load,t} \quad (6)$$

$$Then: P_{Curt,t} = P_{PV,t} + P_{WT,t} - P_{Load,t} \quad (7)$$

With sellback

- Sellback constraint:

$$P_{Sell,t} \geq 0 \quad (8)$$

- Energy balance:

$$P_{PV,t} + P_{WT,t} + P_{Grid,t} = P_{Load,t} + P_{Sell,t} \quad (9)$$

- Energy surplus:

$$If: P_{PV,t} + P_{WT,t} \geq P_{Load,t} \quad (10)$$

$$Then: P_{Sell,t} = P_{PV,t} + P_{WT,t} - P_{Load,t} \quad (11)$$

Renewables fraction (RF):

$$RF = \frac{E_{PV} + E_{WT}}{E_{Load}} \quad (12)$$

- Energy balance:

$$P_{PV,t} + P_{WT,t} + P_{Grid,t} \geq P_{Load,t} \quad (13)$$

In these equations,

N_{PV} is the number of PV modules;

N_{WT} is the number of wind turbines;

Z is the total system cost to be minimized: LCOE (\$/kWh);

$C_{PV,t}$ is the cost of solar power generation at time t (\$/kWh);

$P_{PV,t}$ is the electricity supplied by the PV system at time t (kW);

$C_{WT,t}$ is the cost of wind power generation at time t (\$/kWh);

$P_{WT,t}$ is the electricity supplied by the wind turbine at time t (kW);

$C_{Grid,t}$ is the cost of grid electricity generation at time t (\$/kWh);

$P_{Grid,t}$ is the electricity supplied by the grid at time t (kW);

$P_{Load,t}$ is the electricity demand at time t (kW);

$P_{Sell,t}$ is the surplus electricity sold to the grid at time t (kW);

$P_{Curt,t}$ is the surplus electricity curtailed at time t (kW);

E_{PV} is the yearly electricity generated from PV (kWh);

E_{WT} is the yearly electricity generated from wind turbine (kWh);

E_{Load} is the yearly electricity demand (kWh).

Both the SA and GA optimize problems stochastically. This study runs each algorithm five times

with different randomly generated initial solutions to mitigate the effect of random initialization. The SA algorithm defines an initial temperature of 1000, a final temperature of 1, and a maximum of 500 annealing steps. The variable “temperature” is a control parameter by which the optimization process is governed, where there is still a calculated probability of accepting the suboptimal move. This mechanism is critical for the SA algorithm to escape from local optima, explore larger areas of the solution space, and eventually discover the global optimum. Meanwhile, the initial number of PV and WT units is randomized between 10 and 60. The algorithm stops when the annealing schedule runs out.

The GA’s parameters are fixed throughout all optimization runs as follows: Population size, 30; number of generations, 300; number of parents mating, 4; number of decision variables (genes), 4; gene type, integer; initialization range, 0–60; mutation type, random mutation; mutation probability, 0.5; mutation percentage of genes, 40%; crossover type, uniform crossover; crossover probability, 0.5; parent selection method, steady-state selection (SSS); elitism, six individuals. The optimization process terminates after reaching the maximum number of 300 generations, with no additional convergence-based stopping criterion applied. The final reported solutions for both SA and the GA represent the best configuration obtained from the five independent runs. Additionally, this study uses trimmed mean analysis by excluding the highest and lowest LCOE values and averaging the remaining runs to mitigate the impact of outliers.

2.3. Operational assumptions of the simulated systems

This grid–VRE planning study assumes that the minimum share of electricity generated by renewable energy (the renewable energy fraction) is the only factor that influences the system’s operation, with the system’s (supply) reliability assumed to be 100% at all times (every hour) over one year. The hotel’s electricity demand will be met by on-grid solar PV and/or wind (without any energy storage), with the remaining energy being supplied by the grid to meet the hourly electricity load requirements. For each grid–VRE system combination, the algorithm will determine the LCOE of the potential installed capacity necessary to achieve 100% system reliability. Thus, the optimal system solution is determined by the lowest LCOE that corresponds to the capacity of this grid–VRE combination.

Simulation and operational analysis of renewable energy systems that depict, for example, voltage fluctuations and their impact on grid stability can help grid operators better understand the situation. However, this study focuses on the technical and economic potential of various combinations of grid-dependent renewable energy systems in environments with relatively low wind speeds, specifically their LCOE compared with grid-dependent power sources. As a result, this study does not address system-related operational challenges such as voltage fluctuations or grid stability issues. This is because the simulated grid-connected systems only serve local electricity loads and do not send power to the grid.

2.4. VRE resources and techno-economic data

In this study, hourly temporal solar radiation and wind speed data were collected from <https://power.larc.nasa.gov/data-access-viewer/> for the location defined in Section 2.1. The data gathering process is quite straightforward, as they are available for public access. The process starts by choosing renewable energy in the user community feature and the temporal level option of “hourly” on the web platform, then defining the coordinates of latitude and longitude. For wind and solar data parameters, this study chose “wind speed at 10 meters” and solar irradiation represented by “all-sky surface shortwave

downward irradiation” data (GHI) from January 1, 2021, to December 31, 2023 (covering a 3-year period).

For the simulation, this study averages the obtained 3-year hourly data into a 1-year averaged hourly data for wind and solar individually. These inputs are converted in this study to the estimated hourly electrical power output using the specified formulas for wind and solar, based on Equations 14 and 15, respectively [31,32]. This study does not implement any data bias correction. The maximum output of the rooftop PV, for example, can be calculated by multiplying the panel area, the module’s efficiency, and the total incident irradiance.

$$P_{wind} = C_p \times 0.5 \times \rho \times A \times V^3 \quad (14)$$

$$P_{solar} = GHI \times A_m \times \eta \times PR \quad (15)$$

where:

P_{wind} is the wind turbine’s power output (Watts);

C_p is the power coefficient or Betz limit, taken at 0.42 for a small turbine;

ρ is the air density (1.225 kg/m³);

A is the turbine blade’s swept area (m²);

V is the wind velocity (m/s);

P_{solar} is the power output of solar PV (Watts);

GHI is the global horizontal irradiation (W/m²);

A_m is the solar PV surface area (m²);

η is the solar PV module’s efficiency;

PR is a measure of actual energy output to maximum output under ideal conditions.

The analysis conducted in this optimization study does not consider system losses in the context of power flow losses from the supply to the load, as is commonly discussed in power flow simulation studies. This is in line with the focus of this study, which emphasizes the techno-economic optimization of several possible grid–VRE system combinations. In this study, system losses are considered in the simulation by determining the efficiency of the solar model, the wind turbine’s coefficients, and the inverter’s efficiency.

This study considers three power outputs from wind turbines (3 kW, 5 kW, and 10 kW), in conjunction with a 550-Wp solar PV panel. Furthermore, inverters are included in the systems, and their expense will be integrated into the optimization process. The simulation analyzes different power capacities of the inverter: 9 kW, 15 kW, 18 kW, 22 kW, and 33 kW. Meanwhile, the algorithm for WT and PV electricity generation involves the technical parameters provided above. Figures 4 and 5 illustrate the pseudocodes for obtaining the power output profiles of WT and PV.

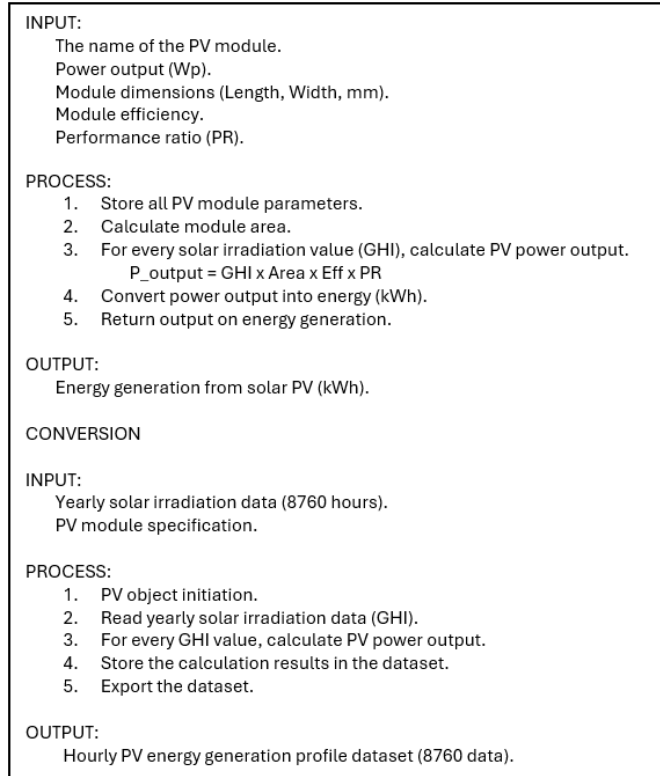


Figure 4. The pseudocode for obtaining PV output.

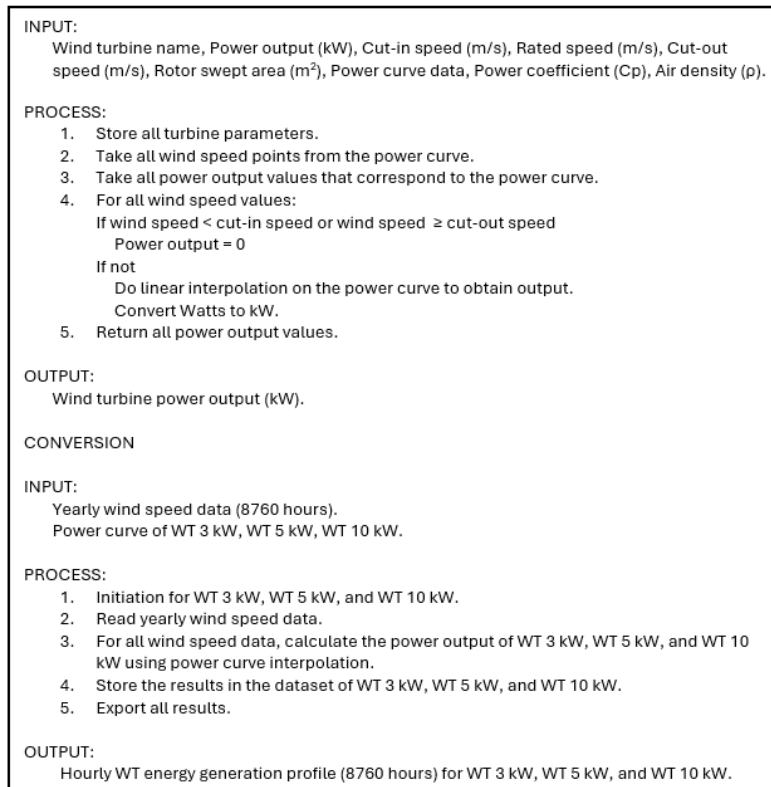


Figure 5. The pseudocode for obtaining WT output.

Table 1 shows the specifications and prices (without batteries) of the commercially available wind turbines involved in this study, as gathered from the manufacturer's website (<https://inkpv.com/wind-turbine-cost/>). The capital costs for wind turbines do not include the battery, as this study does not address the off-grid usage of the system. Meanwhile, the 550-Wp solar PV module has a length and width of 2278 mm and 1134 mm, respectively, with a module efficiency of 21.3% [33], a capital cost of \$289, and an installation cost of \$57.8, including the balance of the system. The prices of inverters, including the system protection devices and cabling, are \$1304 (9 kW), \$1500 (15 kW), \$1665 (18 kW), \$1995 (22 kW), and \$2730 (33 kW). These prices are collected from the locally available inverters on an e-commerce website. The operation and maintenance costs for the wind turbine and PV are assumed to be \$20/kWh and \$10.3/kWh, respectively [34].

Table 1. Technical specifications and prices of the wind turbines.

Specification	WT1	WT2	WT3
Model	Inkpv	Inkpv	Inkpv
Rated power	3 kW	5 kW	10 kW
Cut-in speed	3.5 m/s	4 m/s	4 m/s
Cut-out speed	25 m/s	13 m/s	13 m/s
Rated speed	10 m/s	25 m/s	25 m/s
Swept area	11.34 m ²	20.83 m ²	40.83 m ²
Capital cost	\$3495	\$4765	\$9580
Installation (system) cost	\$699	\$953	\$1,916

The replacement schedule for PV and WT units is assumed to be 25 years and 15 years, respectively, following common practices and the information available from previous studies. This research examines a system lifespan of 25 years, applying a 5% discount rate as a base case. This study does not consider the technical degradation of PV/WT systems, which represents one of its limitations. This simplification is adopted because the research focuses on strategic planning of renewable energy rather than detailed engineering design and operational performance. Consequently, the analysis emphasizes long-term planning pathways, technology deployment, and policy implications instead of component-level degradation mechanisms.

The overall cost of the system, factoring in the net present value (NPV), includes the capital cost for the technology, installation expenses, and the net energy cost from the grid (after deducting the grid's electricity cost from the income generated by reselling electricity to the grid, if applicable). The LCOE for each potential system configuration is calculated by dividing the overall cost by the total energy output of the system. Overall energy production, considering the NPV, is calculated by combining the electricity generation of VRE with the energy supply from the grid.

Electricity tariff escalation is intentionally excluded in the base case simulations, as there is considerable uncertainty surrounding future electricity prices because of regulatory developments, market dynamics, inflation, and energy policies that fall outside the scope of this study. For consistency and transparency purposes, a constant tariff of grid electricity is assumed for the project's lifespan. However, sensitivity analyses are carried out to examine the impact of future tariff changes by applying projections of 110% and 120% of the base case's tariff. To isolate the effect of the electricity export compensation mechanism, we also consider a full (100%) electricity sellback policy, with the discount

rate fixed to 10%. Another scenario evaluates the robustness of the system under unfavorable economic conditions by raising the sellback rate to 100% and raising both the capital costs and installation costs by 25% over the base case's values. This study aims to reveal the sensitivity of the economic performance to variations in the investment costs and remuneration for export and to provide useful implications for the robustness of the proposed system.

3. Results

This section showcases the simulation's outcomes by specifically outlining the techno-economic results of optimizing a potential hybrid grid–VRE supply combination, encompassing the LCOE, renewable energy fraction, and renewable energy generation mix. According to the optimization techniques applied in this research, namely LP, SA, and the GA, the simulation outcomes demonstrate the effects of economic regulation and environmental limitations through varying the allowable energy sellback rates and required renewable energy fractions. This section highlights potential combinations of VRE technologies by examining all considered scenarios and investigating the trade-off between their LCOE and the energy generation mix, while also providing policy recommendations for the hotel industry. Scenarios 1–4 are considered as the base case, while results of the sensitivity analysis are discussed in a separate section afterwards.

3.1. Scenario 1: No sellback rate

This scenario illustrates the current electricity pricing system for renewable energy deployment for domestic customers in Indonesia or other regions that do not compensate for electricity sold back to the grid. Therefore, this scenario evaluates the LCOE for various grid–VRE systems, optimizing potential combinations of grid and VRE technologies concerning the LCOE. The LCOE for the grid in this scenario is \$0.0824/kWh. Figure 6 depicts the LCOE (\$/kWh) of possible grid–VRE systems using all optimization techniques (LP, SA, and GA) in Scenario 1. Meanwhile, Figure 7 illustrates the renewable energy fraction (%) of these possible setups.

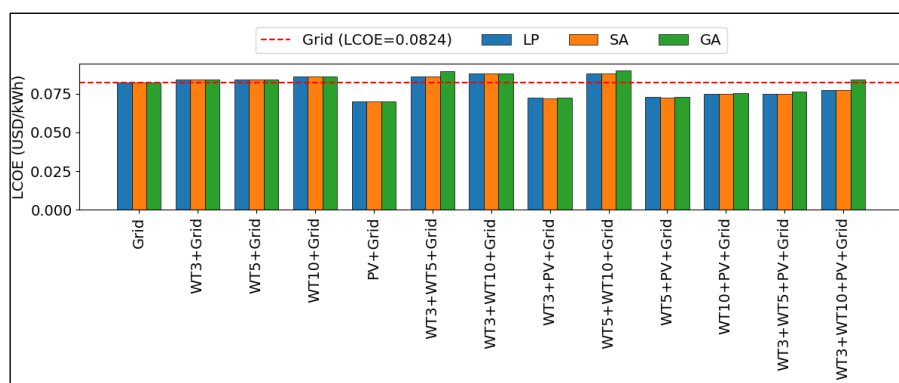


Figure 6. LCOE of possible grid–VRE systems using all optimizations in Scenario 1.

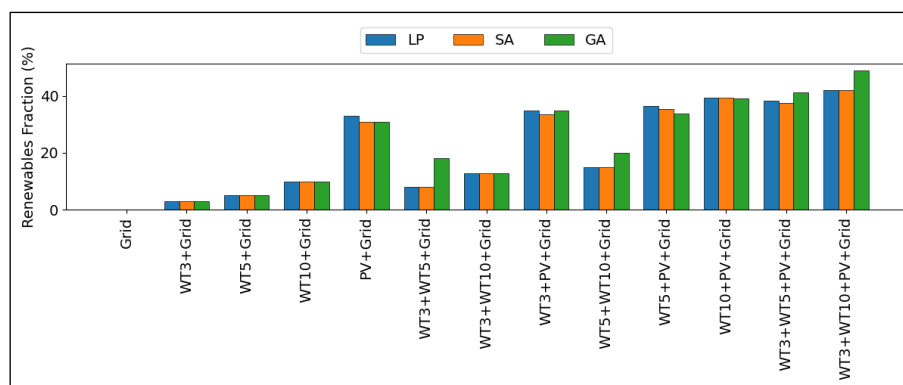


Figure 7. Renewable energy fraction of the possible grid–VRE system using all optimizations in Scenario 1.

Twelve potential grid–VRE system configurations are illustrated in Figure 6. The optimizations yield eight system configurations with comparable or reduced LCOEs relative to the grid’s LCOE. The configurations with a lower LCOE compared with the grid include PV + grid, WT3 + PV + grid, WT5 + PV + grid, WT10 + PV + grid, WT3 + WT5 + PV + grid, and WT3 + WT10 + PV + grid. The LCOE derived from these configurations is \$0.0703/kWh, \$0.0725/kWh, \$0.0728/kWh, \$0.0752/kWh, \$0.0750/kWh, and \$0.0774/kWh, respectively. Furthermore, all optimization methods yield comparable LCOE values across various system configurations, except for the LCOE derived from the GA in the WT3 + WT10 + PV + grid arrangement.

The PV + grid system produces the lowest LCOE, even when compared with grid-only supply. This indicates the cost-effectiveness of solar PV in fulfilling the hotel’s daytime electricity needs. The highest LCOE is achieved by the GA optimization for the WT5 + WT10 + grid setup, at \$0.0900/kWh. Meanwhile, the GA optimization with solar PV (WT3 + WT10 + PV + grid) yields a maximum LCOE of \$0.0845/kWh, which is still comparable with that of the grid. The optimization findings in Scenario 1 suggest that installing small wind turbines can be financially viable in a low-wind speed area, as evidenced by the LCOEs of the WT3 + PV + grid and WT5 + PV + grid configurations, which are solidly lower than the grid’s LCOE, or those of WT3 + grid and WT5 + grid, which resemble the grid’s LCOE.

The renewable energy fractions or, in other words, the share of renewables, as illustrated in Figure 6, range from 3% (WT3 + grid) to 49% (WT3 + WT10 + PV + grid), derived from the GA optimization. A combination of PV and the grid produce a 33% share of renewables. This indicates a considerable role for solar PV in fulfilling the hotel’s power needs throughout the year. The optimization findings show that wind energy contributes much less than solar PV. The setups lacking solar PV achieve a renewable fraction of up to 20%, as demonstrated by the WT5 + WT10 + grid configuration. The greater the capacity of the wind turbine installed, the greater the renewable fraction achieved. Meanwhile, the combination of PV with wind and grid produces approximately 35% to 49%.

Figure 8 shows the energy generation mix (kWh) for every possible grid–VRE system configuration utilizing all optimizations in Scenario 1. The hotel’s annual energy requirement is 83.9 MWh. Provided that there is no unmet energy demand, this overall requirement can be satisfied either by electricity coming exclusively from the grid or through grid–VRE systems. Wind electricity generation varies from 2.4 MWh (WT3 + PV + grid) to 17 MWh (WT3 + WT10 + PV + grid), as obtained by the GA optimization. Wind energy production reaches its peak in the wind and grid configurations (excluding

PV) at 15.2 MWh, specifically in the WT3 + WT5 + grid setup, achieved by the GA optimization. Figure 8 indicates that all optimization methods yield fairly comparable outcomes regarding the energy generation mix, with only minor variations in the energy generation figures when three or more technology combinations are considered.

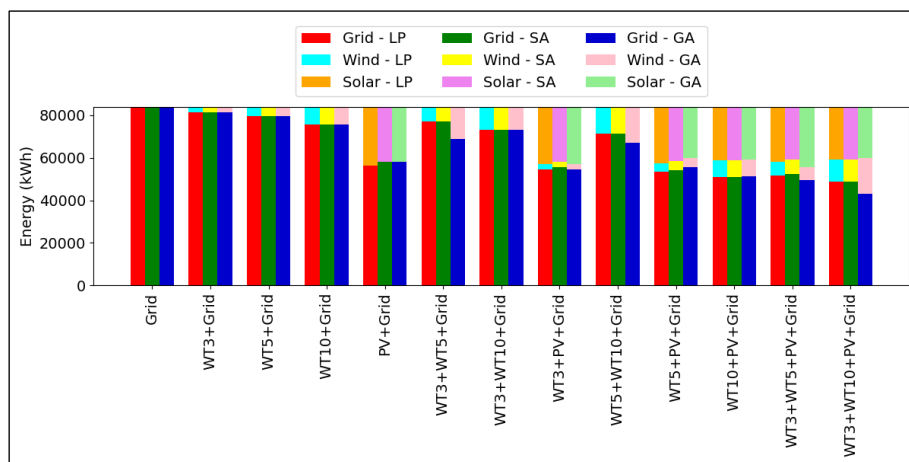


Figure 8. Yearly energy generation mix (kWh) of all possible grid–VRE systems using all optimizations in Scenario 1.

Table 2. Quantity of VRE (units) in possible systems as obtained from all optimizations in Scenario 1.

Possible systems	PV			WT3			WT5			WT10		
	LP	SA	GA	LP	SA	GA	LP	SA	GA	LP	SA	GA
Grid	0	0	0	0	0	0	0	0	0	0	0	0
WT3 + grid	0	0	0	1	1	1	0	0	0	0	0	0
WT5 + grid	0	0	0	0	0	0	1	1	1	0	0	0
WT10 + grid	0	0	0	0	0	0	0	0	0	1	1	1
PV + grid	36	32	32	0	0	0	0	0	0	0	0	0
WT3 + WT5 + grid	0	0	0	1	1	1	1	1	3	0	0	0
WT3 + WT10 + grid	0	0	0	1	1	1	0	0	0	1	1	1
WT3 + PV + grid	35	32	35	1	1	1	0	0	0	0	0	0
WT5 + WT10 + grid	0	0	0	0	0	0	1	1	2	1	1	1
WT5 + PV + grid	34	32	29	0	0	0	1	1	1	0	0	0
WT10 + PV + grid	32	32	31	0	0	0	0	0	0	1	1	1
WT3 + WT5 + PV + grid	33	31	42	1	1	1	1	1	1	0	0	0
WT3 + WT10 + PV + grid	32	32	32	1	1	4	0	0	0	1	1	1

Table 2 shows the number of VRE units in possible systems as obtained from all optimizations in Scenario 1. These VRE systems, based on the wind turbine and solar PV power capacity discussed in Section 2, create the grid–VRE configurations and produce the yearly energy output that satisfies the hotel’s energy requirements. Generally, the optimizations yield only one wind turbine in each grid–VRE system, except that there are three WT5 units required in the WT3 + WT5 + grid setup obtained by the

GA, two WT5 units in the WT5 + WT10 + grid system obtained by the GA, and four WT3 units in the WT3 + WT10 + PV + grid setup, also obtained by the GA. This finding indicates that there is not much contribution that can be provided by wind energy compared with that obtained from PV. However, the two and three WT5 turbines in this optimization generated around 15.2 MWh to 16.8 MWh of electricity with an LCOE of \$ 0.09/kWh and \$0.0897/kWh, respectively. Meanwhile, the four WT3 turbines in the WT3 + WT10 + PV + grid system yield 17 MWh of electricity with an LCOE of \$0.0844/kWh. The other two optimizations in this system configuration, i.e., LP and SA, have one turbine and generate around 10 MWh of electricity.

3.2. Scenario 2: 20% sellback rate

This scenario illustrates the minimal payment that consumers would obtain for selling back their excess electricity to the grid. The results from the optimization present 12 potential grid–VRE system setups, as illustrated in Figure 9, while the LCOE of the grid stays at \$0.0824/kWh. Scenario 2 results in as many as eight potential grid–VRE systems with an LCOE equal to or less than that of the grid alone. These eight system configurations include six systems that exhibit a lower LCOE than the grid, particularly as obtained by the LP and SA optimizations. They are PV + grid, WT3 + PV + grid, WT5 + PV + grid, WT10 + PV + grid, WT3 + WT5 + PV + grid, and WT3 + WT10 + PV + grid, with an LCOE of \$0.0689/kWh, \$0.0718/kWh, \$0.0742/kWh, \$0.07442/kWh, \$0.0737/kWh, and \$0.0765, respectively. Meanwhile, the WT3 + grid and WT5 + grid configurations yield similar LCOEs to the grid, at \$0.0842/kWh and \$0.0842/kWh, respectively.

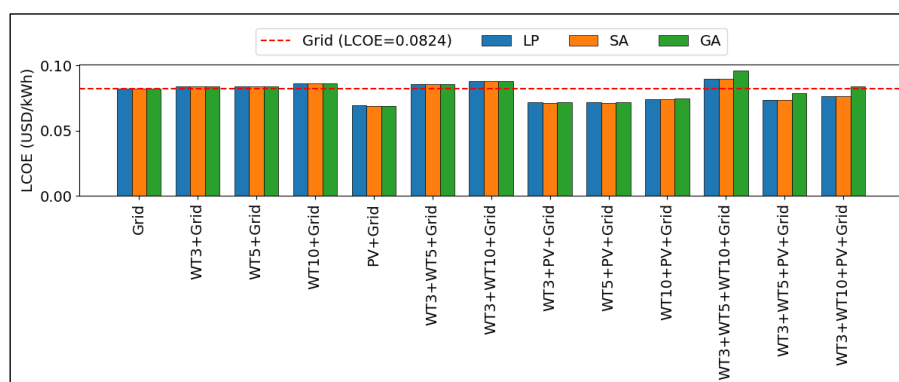


Figure 9. LCOE of possible grid–VRE systems using all optimizations in Scenario 2.

The optimizations of Scenario 2 result in a new configuration of the WT3 + WT5 + WT10 + grid. Scenario 2 yields similar system configurations compared with Scenario 1 in terms of the possible systems with a lower LCOE than the grid. Nevertheless, the LCOE of the PV + grid system drops slightly from \$0.0703/kWh to \$0.0689/kWh, indicating a reduction of \$0.0014/kWh. The LCOEs for the other five setups also decreased. The potential decrease in LCOE when transitioning from Scenario 1 to Scenario 2 is approximately 3–4%. Although there appears to be a slight decrease in the nominal values, the sellback rate would motivate energy consumers to consider transitioning to renewable energy, particularly in the competitive hospitality sector. Meanwhile, Figure 10 presents the renewable energy fractions for the possible grid–VRE system configurations derived from Scenario 2.

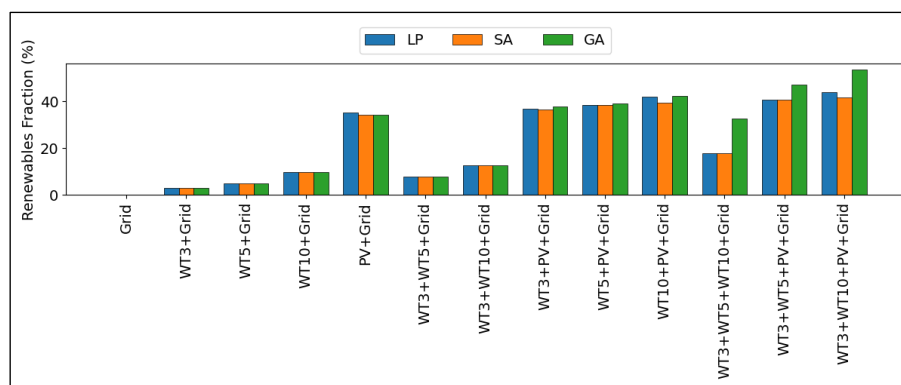


Figure 10. Renewable energy fraction of possible grid–VRE systems using all optimizations in Scenario 2.

The renewable energy fractions in Scenario 2 vary from 3% (WT3 + grid) to a slightly higher 54% (WT3 + WT10 + PV + grid), obtained through GA optimization. The integration of PV and the grid results in a 35.2% share of renewables. A marginally increased proportion of renewables from PV in the PV + grid configuration relative to Scenario 1 (33%) suggests an improved capacity of solar PV in meeting the hotel's energy requirements. The reduced LCOE of PV indicates the need for improvements to harness more energy from solar sources.

Like Scenario 1, the optimization results also indicate that wind energy contributes significantly less than solar PV. Configurations without solar PV reach a renewable fraction of around 17.9% (by LP and SA) to 32.5% (by GA), as shown by the WT3 + WT5 + WT10 + grid setup, and 12.9% (WT5 + WT10 + grid). In the meantime, the integration of PV with wind and grid generates around 41.9% to 53.6%, representing a significant rise compared with the results from Scenario 1, mainly attributed to the sellback rate policy.

Figure 11 displays the annual energy generation mix of every possible grid–VRE system using all optimizations in Scenario 2. With an annual electricity requirement of 83.9 MWh, the hotel can meet its demand with 100% energy satisfaction from all grid–VRE configurations. The solar electricity energy simulation outcomes vary narrowly from 24.9 MWh (WT3 + WT10 + PV + grid) to 29.6 MWh (WT3 + PV + grid and PV + grid configurations). The solar energy production in the PV + grid configuration for Scenario 2 has increased by around 2 MWh compared with Scenario 1.

In Scenario 2, the overall electricity that can be produced by PV across all configurations utilizing the GA, LP, and SA optimizers amounts to 169.1 MWh, 168.8 MWh, and 163.4 MWh, respectively. These accomplishments surpass those achieved in Scenario 1 by around 10%. At the same time, wind energy production increases, as shown by the overall total amount of wind energy generated by all potential configurations. In Scenario 2, the cumulative wind energy production from all configurations acquired through the GA, LP, and SA optimizers is 104.5 MWh, 78 MWh, and 78.5 MWh, respectively, while in Scenario 1, the figures are 95.7 MWh, 76.3 MWh, and 76.4 MWh, respectively.

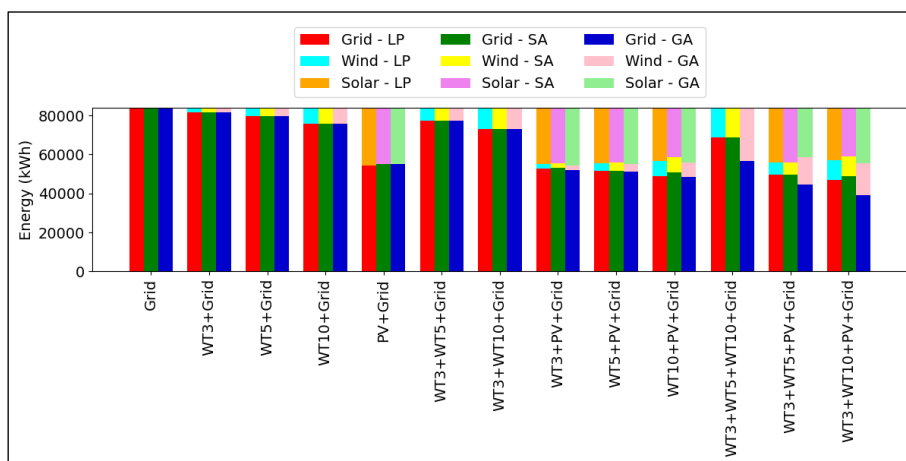


Figure 11. Yearly energy generation mix (kWh) of all possible grid–VRE systems using all optimizations in Scenario 2.

Table 3 presents the count of contributing VRE units across all possible systems derived from all optimizations in Scenario 2. As VRE's electricity generation rises (illustrated in Figure 11), the quantity of VRE's capacity (in units) grows relative to those in Scenario 1. Nonetheless, this is especially true for solar PV capacity. In every conceivable arrangement, PV capacity is enhanced. The sellback rate policy, despite being just 20%, has demonstrated its effectiveness in promoting greater adoption of solar PV. Conversely, the quantity of wind turbines remains the same as in Scenario 1. In each wind system setup, the optimized system consists of only one wind turbine, except for the case of two WT5 and two WT10 turbines in WT3 + WT5 + WT10 + grid, three WT5 turbines in WT3 + WT5 + PV + grid, and two WT10 turbines in WT3 + WT10 + PV + grid, indicating that this is the most cost-effective solution relative to other alternatives, considering the low wind resource.

Table 3. Quantity of VRE (units) in possible systems as obtained by all optimizations in Scenario 2.

Possible systems	PV			WT3			WT5			WT10		
	LP	SA	GA	LP	SA	GA	LP	SA	GA	LP	SA	GA
Grid	0	0	0	0	0	0	0	0	0	0	0	0
WT3 + grid	0	0	0	1	1	1	0	0	0	0	0	0
WT5 + grid	0	0	0	0	0	0	1	1	1	0	0	0
WT10 + grid	0	0	0	0	0	0	0	0	0	1	1	1
PV + grid	43	40	40	0	0	0	0	0	0	0	0	0
WT3 + WT10 + grid	0	0	0	1	1	1	0	0	0	1	1	1
WT3 + WT5 + grid	0	0	0	1	1	1	1	1	1	0	0	0
WT3 + PV + grid	41	40	45	1	1	1	0	0	0	0	0	0
WT5 + PV + grid	41	40	43	0	0	0	1	1	1	0	0	0
WT10 + PV + grid	39	32	41	0	0	0	0	0	0	1	1	1
WT3 + WT5 + WT10 + grid	0	0	0	1	1	1	1	1	2	1	1	2
WT3 + WT5 + PV + grid	40	40	35	1	1	1	1	1	3	0	0	0
WT3 + WT10 + PV + grid	38	32	53	1	1	1	0	0	0	1	1	2

3.3. Scenario 3: 50% sellback rate

Scenario 3 illustrates the relatively higher compensation that customers would receive by selling their surplus electricity back to the grid. The 50% sellback rate indicates that the utility will compensate customers with 50% of the overall monetary worth per kWh of electricity supplied to the grid during a specific time frame, typically calculated monthly. Figure 12 depicts the impact of a 50% electricity sellback rate on the possible system configurations' LCOE.

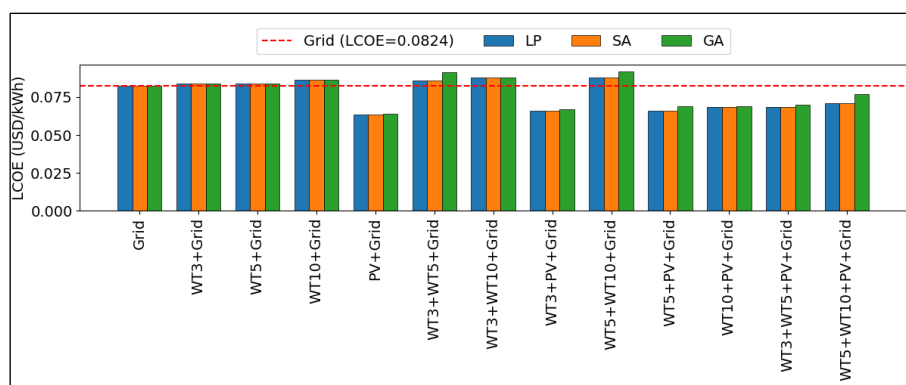


Figure 12. LCOE of possible grid–VRE systems using all optimizations in Scenario 3.

The results from the simulation in Scenario 3 indicate that all LCOEs for the potential grid–VRE systems are continuing to decline, with the majority of configurations demonstrating an LCOE below \$0.077/kWh. Six system setups exhibit an LCOE significantly lower than that of the grid, namely PV + grid (\$0.0636/kWh), WT3 + PV + grid (\$0.0658/kWh), WT5 + PV + grid (\$0.0661/kWh), WT10 + PV + grid (\$0.0687/kWh), WT3 + WT5 + PV + grid (\$0.0683/kWh), and WT5 + WT10 + PV + grid (\$0.0768/kWh). The outcomes emphasize the increased importance of PV in the energy generation mix and the more competitive wind energy achieved by using small wind turbines.

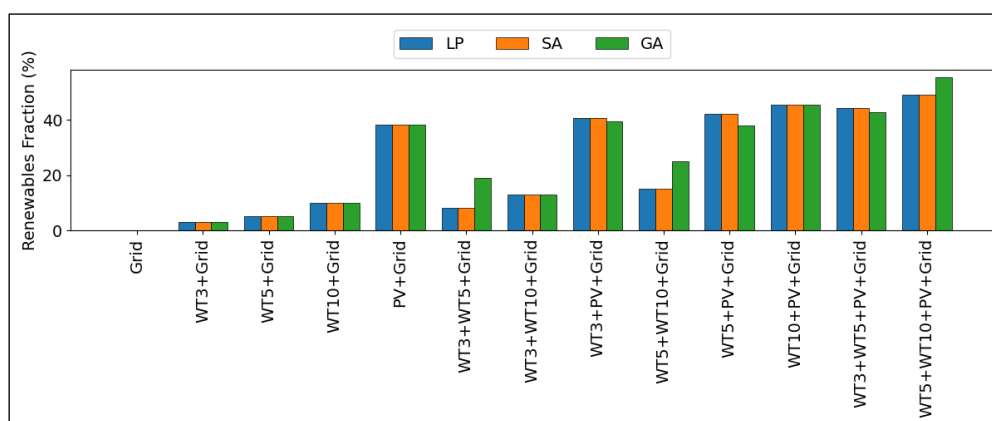


Figure 13. Renewable energy fraction of possible grid–VRE systems using all optimizations in Scenario 3.

Meanwhile, Figure 13 illustrates the renewable energy fractions of possible grid–VRE systems that utilize all optimizations in Scenario 3. Out of the 12 grid–VRE system setups, the WT5 + WT10 + PV + grid configuration achieves the highest renewable energy fraction of approximately 55.3% (according to the GA optimization). The renewables fraction in the PV + grid configuration for Scenario 3 is higher than that of Scenario 2 (38.4%). The integration of PV and wind-generated renewable fractions exceeds 40%. This suggests a more advanced role of VRE in the system while keeping the LCOE equal to or lower than that of the grid.

Figure 14 shows the annual energy generation mix of possible grid–VRE systems using all optimizations in Scenario 3. The WT5 + WT10 + PV + grid configuration yields 17.9 MWh of wind electricity generation while maintaining a preferred LCOE of \$0.077/kWh (lower than the grid). The PV + grid setup yields as much as 32.2 MWh of annual electricity to assist in fulfilling the hotel’s annual electricity demand. Meanwhile, it was found that the WT5 + WT10 + grid setup produces around 21 MWh of wind-generated electricity (as obtained by the GA), marking the peak wind electricity output among the possible grid–VRE systems, although the LCOE is higher than that of the grid. Figure 13 similarly emphasizes an increased percentage of PV and wind within the generation mix, showing a minor decline in the grid’s output.

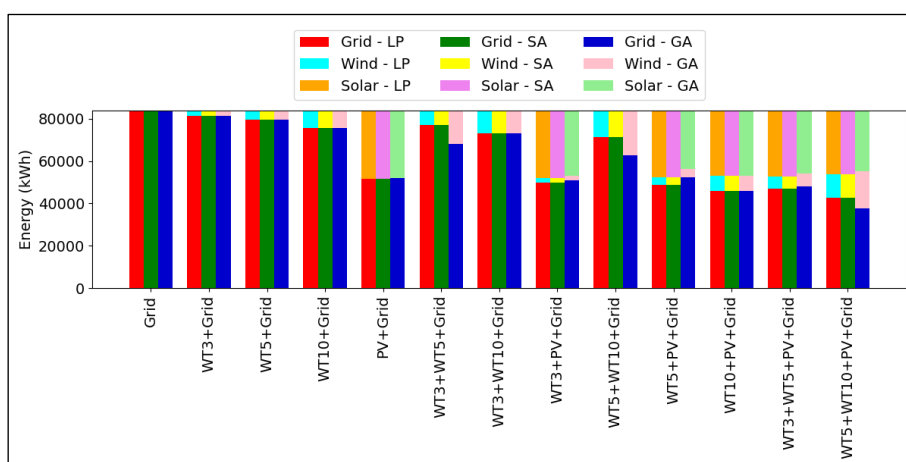


Figure 14. Yearly energy generation mix (kWh) of possible grid–VRE systems using all optimizations in Scenario 3.

Table 4 presents the unit quantity of VRE technologies in possible systems as obtained from all optimizations in Scenario 3. The results seem to change compared with Scenario 2, especially in terms of the penetration of solar PV capacity, which increases to 60 modules. This shows that PV stands out as the leading technology, with LP and SA opting for 60 units in almost every configuration, whereas the GA produces slightly fewer units (from 38 to 59 units), indicating its inclination to vary solutions. In the case of wind options, the GA optimization yields slightly higher wind capacity compared with LP and SA. These include three WT3 turbines and two WT5 turbines in the WT3 + WT5 + grid system, and three WT5 turbines in the WT5 + WT10 + grid system. Wind is also present in combinations of the grid and PV. In the WT5 + WT10 + PV + grid, for example, there are three WT5 turbines despite plenty of PV units being present in the system. This implies a possibility of wind resources being involved in the grid–VRE system for greater wind power capacity.

Table 4. Quantity of VRE (units) in possible systems as obtained by all optimizations in Scenario 3.

Possible systems	PV			WT3			WT5			WT10		
	LP	SA	GA	LP	SA	GA	LP	SA	GA	LP	SA	GA
Grid	0	0	0	0	0	0	0	0	0	0	0	0
WT3 + grid	0	0	0	1	1	1	0	0	0	0	0	0
WT5 + grid	0	0	0	0	0	0	1	1	1	0	0	0
WT10 + grid	0	0	0	0	0	0	0	0	0	1	1	1
PV + grid	60	60	59	0	0	0	0	0	0	0	0	0
WT3 + WT5 + grid	0	0	0	1	1	3	1	1	2	0	0	0
WT3 + WT10 + grid	0	0	0	1	1	1	0	0	0	1	1	1
WT3 + PV + grid	60	60	53	1	1	1	0	0	0	0	0	0
WT5 + WT10 + grid	0	0	0	0	0	0	1	1	3	1	1	1
WT5 + PV + grid	60	60	38	0	0	0	1	1	1	0	0	0
WT10 + PV + grid	60	60	59	0	0	0	0	0	0	1	1	1
WT3 + WT5 + PV + grid	60	60	49	1	1	1	1	1	1	0	0	0
WT5 + WT10 + PV + grid	60	60	55	0	0	0	1	1	3	1	1	1

As seen in Table 4, more intricate hybrid systems exhibit greater complementarities: WT3 + WT5 + PV + grid sustains elevated PV counts (60 for LP and SA; 37 for GA) while also incorporating one unit each of WT3 and WT5. Likewise, WT3 + WT10 + PV + grid results in significant PV deployment (60 for LP and SA; 29 for GA) with one to two wind units, according to this approach. The results underscore the steady emphasis on PV as the core of efficient systems, whereas wind turbines act as additional components to improve systems' variety and resilience.

3.4. Scenario 4: 25% renewable energy fraction

This scenario assesses the impact of a mandatory regulatory policy on the renewable energy share on the techno-economic performance of the systems. The LP, SA, and GA optimizations model a 25% share of renewable energy (renewable energy fraction), representing the minimum proportion of electricity production from renewable sources required to meet the hotel's yearly energy needs. The optimization findings indicate the LCOE of possible grid–VRE configurations, along with the annual energy production composition and the number of units in those systems. The simulations yield eight possible system configurations, namely WT3 + grid, WT5 + grid, PV + grid, WT3 + WT5 + grid, WT3 + WT10 + grid, WT5 + WT10 + grid, WT5 + PV + grid, and WT10 + PV + grid.

Figure 15 illustrates the LCOE of possible grid–VRE systems using all optimizations in Scenario 4. Implementing a minimum renewable energy share resulted in changes to the LCOE across various system setups. The lowest LCOE is achieved with the PV + grid arrangement at \$0.0713/kWh, whereas the other two systems that include PV, specifically WT5 + PV + grid and WT10 + PV + grid, result in \$0.0751/kWh and \$0.0794/kWh, respectively. The possible systems that include wind and the grid (WT3 + grid, WT5 + grid, WT3 + WT5 + grid, WT3 + WT10 + grid, WT5 + WT10 + grid, WT5 + PV + grid, and WT10 + PV + grid) result in \$0.0987/kWh, \$0.0916/kWh, \$0.0935/kWh, \$0.0939/kWh, \$0.0919/kWh, \$0.0751/kWh, and \$0.0794/kWh, respectively. The LCOEs in Scenario 4 exceed those in Scenario 3 (a sellback rate of 50%). This suggests requiring a minimum share of renewable energy in

grid–VRE setups, considering that the VRE resources in low-wind regions are not as efficient as the sellback rate or feed-in tariff policies.

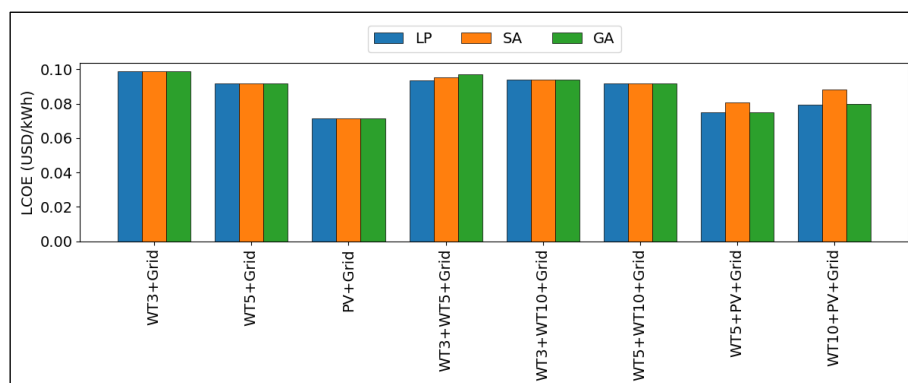


Figure 15. LCOE of possible grid–VRE systems using all optimizations in Scenario 4.

The LCOE of the PV + grid arrangement in this case (\$0.0713/kWh) is close to that in Scenario 1. Nonetheless, the role of solar energy is limited to about 25%, in contrast to 33% in Scenario 1, compelling the optimizations to opt for energy generation from the grid. For the WT3 + WT5 + grid in Scenario 4, an increased LCOE results from enforcing substantial wind energy production under low-wind speed conditions. Relative to the identical configuration in Scenario 1, the notably increased LCOE is primarily attributed to the substantial wind penetration, which stands at about 35% compared with 62 MWh for solar.

Figure 16 depicts the renewable fractions of seven potential grid–VRE systems in Scenario 4. Given that VRE penetration levels are imposed to approximately a minimum of 25–26% of the overall systems' setup, the energy generation mix for each configuration is similarly constrained, as highlighted by the considerable share of PV compared with wind when PV is included in the system, as shown in Figure 17. The generated wind energy rises to approximately 21.0 MWh to 22.3 MWh for all wind and grid configurations, given the low-wind conditions. However, these energy generation systems have resulted in LCOEs of \$0.091/kWh to \$0.098/kWh, which are still comparable with those of Scenarios 1 to 3.

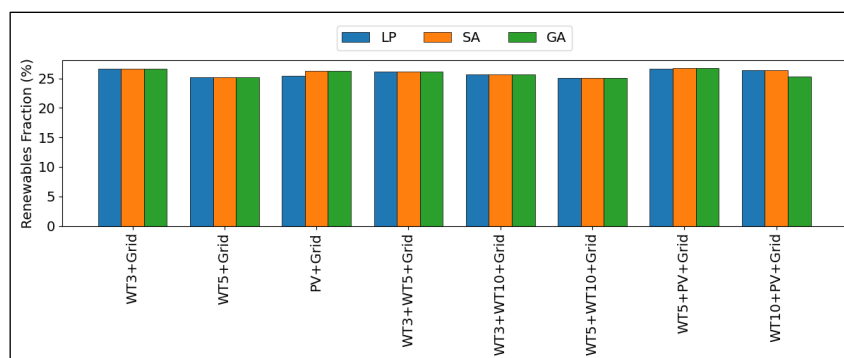


Figure 16. Renewable energy fraction of possible grid–VRE systems using all optimizations in Scenario 4.

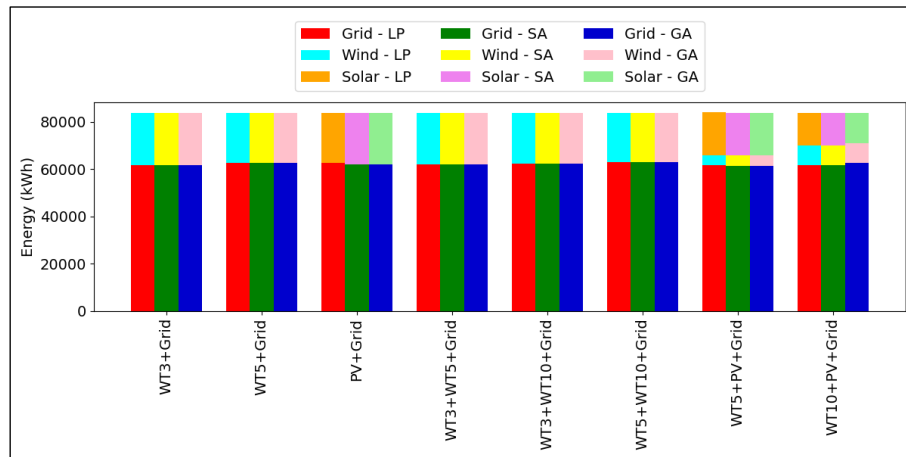


Figure 17. Yearly energy generation mix (kWh) of possible grid–VRE systems using all optimizations in Scenario 4.

Table 5 displays the unit count of five potential systems derived from all optimizations in Scenario 4. The solar PV capacity has been reduced to 21 to 25 units because of the maximum limits on renewable energy. Conversely, the quantity of wind turbines expands (reaching up to eight units of WT3 and five units of WT5) to meet the mandatory requirement for 25% renewable energy integration.

Table 5. Quantity of VRE units in possible systems as obtained by all optimizations in Scenario 4.

Possible systems	PV			WT3			WT5			WT10		
	LP	SA	GA	LP	SA	GA	LP	SA	GA	LP	SA	GA
WT3 + grid	0	0	0	0	0	0	9	9	9	0	0	0
WT5 + grid	0	0	0	0	0	0	5	5	5	0	0	0
PV + grid	24	25	25	0	0	0	0	0	0	0	0	0
WT3 + WT5 + grid	0	0	0	2	2	2	4	4	4	0	0	0
WT3 + WT10 + grid	0	0	0	2	2	2	0	0	0	2	2	2
WT5 + WT10 + grid	0	0	0	3	3	3	0	0	0	1	1	1
WT5 + PV + grid	20	20	20	0	0	0	1	1	1	0	0	0
WT10 + PV + grid	15	15	14	0	0	0	0	0	0	1	1	1

In Scenario 4, with a 25% renewable energy share mandated, the optimization findings indicate a strong inclination toward systems that integrate PV and wind technologies with the grid. The PV + grid setup consistently displays a high installation rate of PV units (24–25), underscoring the leading role of solar energy in fulfilling the renewable energy quota. Likewise, mixed setups like WT5 + PV + grid and WT10 + PV + grid show significant PV integration (14–20 units) with just a single wind turbine in every optimization, signifying that solar continues to be the main contributor. The WT5 + grid setup, on the other hand, depends solely on five wind turbines (WT5), similar to the WT3 + grid system with nine wind turbines. The WT3 + WT5 + grid alternative combines two smaller wind turbines with four larger ones. In summary, the findings highlight that solar PV represents the most economical and dependable choice to reach the 25% renewable energy target, while wind serves as a

supplementary option. Nevertheless, the contribution of wind energy can be raised to 25% when combined with the grid, without PV, and given the imposed minimum renewable energy fraction.

3.5. Synthesis of the base case results

The results obtained from all scenarios can be synthesized into three comprehensive aspects: (1) Resource dynamics and the primacy of solar PV, (2) incentives versus mandates, and (3) algorithmic fidelity and strategic insight for the industry. For the first aspect, looking closely at the system's behavior in all four scenarios, solar PV consistently emerges as the economic anchor of the hotel's energy transition. Wind assets in most places in Indonesia face severe structural headwinds due to a low wind profile. When left to pure market conditions with no grid compensation (Scenario 1), a standalone PV-grid setup optimizes to an LCOE of \$0.0703/kWh, comfortably beating the baseline grid tariff of \$0.0824 per kWh. In contrast, wind energy operates entirely on the margins. Small wind turbines provide some resource diversification, but their capital costs are difficult to justify on their own. They produce minor energy fractions unless forced into the mix by external regulatory pressures or boosted by aggressive policy mechanisms.

The second aspect, contrasting export incentives (Scenarios 2 and 3) with regulatory quotas (Scenario 4), shows a clear trend. A modest 20% sellback rate immediately changes the system's architecture, reducing LCOEs by 3–4% and increasing the adoption of solar. With the incentive at 50% (Scenario 3), the algorithms raise solar capacity to the 60-unit threshold in almost all optimization routines, bringing the LCOE down to \$0.0636/kWh. In contrast, a hard 25% renewable energy mandate without sellback (Scenario 4) distorts the economic landscape. In configurations with no solar availability (wind-only tracks), the optimizers are forced to over-index on wind assets, stacking up to nine turbines in some cases, to meet this mandatory target. This artificial inflation brings the LCOE to \$0.0987/kWh, a heavy penalty over grid parity. This sharp contrast provides an important policy insight: Market-enabling frameworks such as net metering are far more effective at driving affordable decarbonization in the hospitality sector than rigid structural mandates that ignore local resource constraints.

From a computational perspective, the high level of convergence of LP, SA, and the GA provides strong validation of these findings. Across most runs, all three mathematical approaches settle on remarkably similar asset allocations and generation profiles. The slight variances observed within the GA's outputs actually highlight their unique strength. Because GA is highly adept at navigating nonlinear, multivariable spaces, it occasionally uncovers distinct alternative pathways, such as intensifying wind unit counts to push the renewable fraction past 54% in Scenario 2 with only a negligible cost penalty. The hotel operators could then prioritize immediate, aggressive rooftop solar deployment to secure low-hanging cost savings. The integration of wind should remain secondary, pursued primarily as a resilience play or when local utility rules shift toward high-reward grid buyback schemes.

3.6. Synthesis of the sensitivity and extended scenario-based analyses' results

This subsection summarizes and shows the optimization results for several scenarios in addition to the base case scenarios (Scenarios 1–4) described earlier. These include Scenario 5 (100% sellback rate), Scenario 6 (100% sellback rate with capital and installation costs increased by 25%),

Scenario 7 (100% sellback with a discount rate of 10%), Scenario 8 (100% sellback with an increased electricity tariff of 10%), and Scenario 9 (100% sellback with an increased electricity tariff of 20%). All the algorithms tested show quite similar results in terms of the LCOE and renewable energy fraction. Therefore, the following sensitivity analysis presents optimization by the GA and compares the results with the base case scenarios. Table 6 summarizes the effect of varying the electricity sellback rate on the optimized system. The analysis is performed by changing only the sellback rate from 0% to 100% (Scenarios 1–3 and 5), while keeping all other input parameters unchanged, including the discount rate of 5%. This one-factor-at-a-time sensitivity analysis provides a clear indication of how the export compensation policy influences the LCOE and the economic viability of the proposed system.

Meanwhile, Table 7 presents a comparison of the LCOE across the extended scenarios (Scenarios 5–9). These scenarios explore the effects of different economic and policy assumptions, including changes in the electricity sellback rate, capital and installation costs, discount rate, and grid electricity tariff. Rather than representing a conventional sensitivity analysis, this comparison indicates how the optimized system performs under a range of plausible future conditions, allowing its economic robustness to be evaluated relative to the base case scenarios.

The sensitivity analysis reveals that the rate of electricity sellback is an important factor for the better economic performance of PV-integrated systems, but it has a limited impact on wind-dominated configurations. Table 6 shows that the standalone PV + grid system has a reduction in the LCOE from \$0.07011/kWh to \$0.05268/kWh when the sellback rate increases from 0% to 100%, which is a ~25% improvement. The same trend is also seen for the hybrid systems with PV, i.e., WT3 + PV + grid, WT5 + PV + grid, WT10 + PV + grid, and WT5 + WT10 + PV + grid, where the LCOE is significantly reduced with increasing sellback rates. Such improvements contribute to the enhanced economic value of surplus PV generation, with excess electricity being sold to the grid at more favorable compensation rates. All sellback scenarios for systems made up entirely of wind turbines exhibit almost the same LCOE values, indicating that their economic performance is rather insensitive to changes in remuneration for export. This behavior is probably due to the less frequent surplus electricity exports caused by the more variable wind resource and the installed optimal system capacities. Overall, the results suggest that the improvement of the sellback policy is mainly to improve the economic competitiveness of the PV-based hybrid system, thereby facilitating the adoption of distributed solar generation.

The extended scenario-based analysis validates the economic feasibility of the optimized system under a range of alternative economic assumptions, although the impact varies significantly across the scenarios. For almost all system configurations, Scenario 6 (a 25% increase in capital and installation costs) shows the greatest increase in the LCOE, reflecting the dominance of the initial investment costs on the long-term project economics. The LCOE also increases when the discount rate is increased from 5% to 10% (Scenario 7), although the effect is generally less pronounced than the effect of higher investment costs, indicating that the proposed systems are moderately sensitive to the financing conditions. Different responses are obtained when the electricity tariff on the grid varies. Scenario 8 (a 10% tariff increase) results in moderate increases in the LCOE and, in some cases, changes the optimal system configuration, indicating that increased grid electricity prices affect the trade-off between renewable generation and grid electricity. In Scenario 9 (a 20% tariff increase), some other previously optimal configurations are no longer selected, and the remaining systems have the highest LCOE values in all scenarios. These results show that the proposed hybrid systems are

technically feasible, but their economic performance is highly dependent on future investment costs and electricity price policies. Thus, it is likely to be important to preserve good investment conditions as well as adequate mechanisms to compensate for exports so as to maintain the economic attractiveness of hybrid renewable energy systems.

Table 6. Comparison of LCOE (\$/kWh) for various sellback rate scenarios using the GA with a 5% discount rate.

Possible systems	Scenario 1	Scenario 2	Scenario 3	Scenario 5
PV + grid	0.0701	0.0689	0.0638	0.0527
WT3 + grid	0.0842	0.0842	0.0842	0.0842
WT5 + grid	0.0842	0.0842	0.0842	0.0842
WT10 + grid	0.0863	0.0863	0.0863	0.0863
WT3 + WT5 + grid	0.0898	0.0860	0.0915	0.0879
WT3 + WT10 + grid	0.0881	0.0881	0.0881	0.0881
WT3 + PV + grid	0.0725	0.0719	0.0669	0.0551
WT5 + WT10 + grid	0.0881	N/A	0.0919	N/A
WT5 + PV + grid	0.0729	0.0722	0.0692	0.0568
WT10 + PV + grid	0.0752	0.0749	0.0689	0.0566
WT3 + WT5 + PV + grid	0.0766	0.0789	0.0699	0.0639
WT3 + WT10 + PV + grid	0.0845	0.0839	N/A	0.0678
WT5 + WT10 + PV + grid	N/A	N/A	0.0770	0.0637
WT3 + WT5 + WT10 + grid	N/A	0.0960	N/A	N/A

Table 7. Comparison of LCOE (\$/kWh) for scenarios involving 100% sellback rates using the GA.

Possible systems	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
PV + grid	0.0527	0.0716	0.0638	0.0666	N/A
WT3 + grid	0.0842	0.0875	0.0861	0.0941	0.1021
WT5 + grid	0.0842	0.0888	0.0869	0.0947	0.1025
WT10 + grid	0.0863	0.0954	0.0917	0.0991	0.1065
WT3 + WT5 + grid	0.0879	N/A	0.0997	0.1018	0.1058
WT3 + WT10 + grid	0.0881	0.1006	0.1030	N/A	0.1098
WT3 + PV + grid	0.0551	0.0778	0.0725	0.0711	0.0762
WT5 + WT10 + grid	N/A	0.1019	N/A	N/A	0.1139
WT5 + PV + grid	0.0568	0.0785	0.0745	0.0763	0.0783
WT10 + PV + grid	0.0566	0.0855	N/A	0.0761	0.0812
WT3 + WT5 + PV + grid	0.0639	N/A	0.0797	N/A	N/A
WT3 + WT10 + PV + grid	0.0678	0.0963	N/A	N/A	N/A
WT5 + WT10 + PV + grid	0.0637	0.0959	0.0799	N/A	N/A
WT3 + WT5 + WT10 + grid	N/A	N/A	N/A	N/A	N/A

4. Discussion

Table 6 shows the comparison of average LCOEs obtained by the LP, SA, and GA optimizations across all base case scenarios (Scenarios 1–4) for the systems with PV. These are acquired through systems that include PV. PV + grid consistently yields the lowest costs in all scenarios, with the average LCOE ranging from \$0.0637 to \$0.0714/kWh, all below the grid-only benchmark of \$0.0824/kWh, including the scenario with a 25% renewable energy fraction (Scenario 4). This implies that the most economical option across all policy frameworks in the study context is to integrate solar PV. Systems that combine wind turbines (WT3, WT5, or WT10) with PV and the grid show higher LCOE values (0.0662–0.0798/kWh), which are still lower than the grid's cost. This suggests that wind–PV–grid combinations are not only technically feasible but also economically competitive. The sellback policy in Scenarios 2 and 3 provides further financial incentive for projects with the wind–PV–grid configuration.

Table 8. Comparison of the average LCOE (\$/kWh) from LP, SA, and the GA in all base case scenarios.

Grid–VRE systems	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV + grid	0.0701	0.0691	0.0637	0.0714
WT3 + PV + grid	0.0724	0.0716	0.0662	N/A
WT5 + PV + grid	0.0727	0.0719	0.0671	0.0751
WT10 + PV + grid	0.0752	0.0745	0.0688	0.0796
WT3 + WT5 + PV + grid	0.0754	0.0754	0.0688	N/A
WT3 + WT10 + PV + grid	0.0798	0.0789	N/A	N/A

With costs lower than the grid in Scenario 4, the wind–PV–grid systems (WT5 + PV + grid and WT10 + PV + grid) provide feasible techno-economic alternatives to meeting the hotel's electricity demand with a similar LCOE to the PV + grid system within the same scenario and given the required renewable energy penetration under low-wind speed conditions. There is a trade-off in terms of wind and solar electricity generation in wind–PV–grid configurations. The wind and solar electricity generation level is found to be 4.2 MWh and 18.2 MWh per year, respectively, in the WT5 + PV + grid system. The generated wind electricity increases to 8.3 MWh while solar electricity declines to 12.9 MWh in the WT10 + PV + grid system. The results indicate that strict renewable fraction (minimum) limits without supporting market mechanisms (Scenario 4) can still work, particularly in possible wind–PV–grid systems. However, possible wind–grid configurations require supporting market mechanisms, as their LCOEs are found to be higher than that of the grid. Policies that allow higher sellback rates (Scenarios 2 and 3) significantly increase the economic appeal of renewables.

The study finds that enhancing the acceptance and incorporation of VRE necessitates government action via effective market mechanisms, particularly in sectors such as hospitality that are energy-intensive and prominently showcase sustainability pledges. Small wind turbines remain beneficial, especially in low-wind areas where they can effectively support grid–VRE systems, despite solar PV proving to be the most cost-effective option. Nonetheless, the simple and inexpensive electricity tariff systems found in numerous developing countries frequently obstruct the implementation of these hybrid solutions, complicating efforts to create a persuasive financial argument for investment without extra incentives.

Table 9 presents a comparison of computational times for LP, SA, and the GA across four different

scenarios for the base case. The findings show that LP always had the fastest computation, with speeds between 54.35 seconds and 162.16 seconds. This was far better than both SA and the GA. LP had the fastest computation in Scenario 1 (no sellback), and Scenario 4 (25% renewable energy fraction) had the slowest computation, which was due to the model becoming more complex. SA and the GA, on the other hand, took substantially longer to process because their search procedures were iterative and random. In Scenario 3 (50% sellback rate), the GA took the longest, with a peak time of 772.18 seconds. In most cases, SA worked a little better than the GA, but both approaches were far slower than LP. Overall, the results show that LP is better at computing, which makes it better for optimization tasks that need to be done quickly than the metaheuristic methods.

Table 9. Comparison of computational time (seconds) between LP, SA, and the GA in all base case scenarios.

Scenario	LP	SA	GA
Scenario 1: No sellback	54.35	408.69	621.57
Scenario 2: 20% sellback rate	63.13	395.15	372.34
Scenario 3: 50% sellback rate	59.22	453.02	772.18
Scenario 4: 25% renewable energy fraction	162.16	431.18	673.39

4.1. Limitations and the role of energy storage

An important limitation of this study is the lack of battery storage and demand response in the modeled scenarios. The influence of battery storage on systems' performance and investment decisions is significant and varies with the tariff design and policy context. Low or nonexistent sellback rates can make batteries crucial for hotels to utilize more of their solar and wind power, thus reducing grid dependence and energy waste.

Conversely, with high sellback rates, the incentive to store energy diminishes, favoring energy export. Storage gains importance when differences between peak and off-peak prices are large or when there are limits on grid exports. An optimal system would feature higher PV and wind capacity, greater grid independence, and easy compliance with renewable energy standards, particularly with the addition of battery storage or demand response. Future research on these aspects is needed for optimizing hybrid renewable systems' design.

4.2. Scenario interpretations and actionable insights for decision-makers

This analysis of the grid of an Indonesian island (Bali as a case study) for small hotels shows that the most cost-effective and practical on-grid solution for all cases is a PV + grid with about 32–60 PV units, depending on the sellback rates and local policies. Solar PV remains the largest contributor to both cost reductions and renewable energy goals. Wind turbines are only economically viable under policy constraints, either with strong renewable energy requirements or high sellback rates. In these cases, systems may need up to nine WT3 or five WT5 units to meet the minimum renewable shares.

The results reveal clear policy thresholds. (1) A sellback rate of 20% reduces the system's costs (LCOE) by roughly 3–4% and greatly increases PV adoption. (2) Hotels can maximize PV deployment (up to 60 units) and lower their LCOE to \$0.0636/kWh, well below the grid-only cost,

with a 50% sellback rate. (3) Conversely, a strict 25% renewable mandate with no sellback pushes the system toward wind-heavy setups, which meet the quota but at higher costs (the LCOE is up to \$0.0987/kWh). The results show that market-based incentives such as net metering, feed-in tariffs, or dynamic pricing are much more effective and appealing for the adoption of renewables than rigid quotas, especially in areas with low wind resources. In many developing countries, however, simple and low electricity tariffs often prevent the financial attractiveness of hybrid systems, and government intervention is thus essential.

Government action will be needed to overcome these barriers and to increase the acceptance of VRE, particularly in energy-intensive sectors such as hospitality. Renewable energy investments can be made more financially viable through policies such as feed-in tariffs, net metering, and dynamic pricing. These strategies will help speed up sustainable energy transitions, as well as support the business case for renewables across the hospitality sector. What is ultimately needed are effective regulations and policy frameworks that enable successful technological adoption and broader societal benefits.

From the decision-making point of view, the sensitivity and extended scenario analyses show that policy measures for export-related compensation and investment support are more effective than relying only on future electricity price increases to improve the economic viability of hybrid renewable energy systems. The results in Tables 6 and 7 consistently underscore the role of fair export compensation mechanisms to accelerate distributed solar deployment, with PV-integrated configurations benefiting substantially from higher sellback rates. Meanwhile, the high sensitivity of LCOE to capital and installation costs underlines the importance of investment incentives, like capital subsidies, low-interest financing, or tax incentives, to lighten the financial burden of project development. The results provide policymakers and investors with practical guidance on which economic levers most influence the adoption of renewable energy and the long-term competitiveness of projects.

This study assumes ideal grid reliability, where all designs can satisfy the annual hotel demand without interruption. In practice, island grids could be interrupted more often. Where reliability is a concern, hotels may want to consider adding PV, wind, or storage capacity. The recommendations here establish a baseline for reliable grids, but less reliable grids may need adjustments.

5. Conclusions

This research evaluates the techno-economic viability of enhancing grid-VRE assets to improve energy sustainability in small hotels located in regions with low wind resources. This research uses the LP, SA, and GA optimization techniques to determine the LCOE, renewable energy ratios, and energy generation combinations for potential grid-VRE system setups, drawing on a case study of a proposed small hotel on Nusa Penida Island in Bali, Indonesia, characterized by high solar availability but limited wind resources. This research examines four energy provision scenarios to demonstrate the impacts of market incentives and environmental limitations. These scenarios include no sellback, a 20% sellback rate, a 50% sellback rate, and a 25% renewable energy fraction.

The findings indicate that the PV-grid setups across all scenarios exhibit the lowest LCOE in comparison with any potential arrangements that include PV and small wind turbines (3 kW, 5 kW, and 10 kW), with Scenario 1 yielding the most affordable LCOE among them. Next are several wind-PV-grid systems that generate lower LCOEs than the grid or below \$0.0824/kWh. Scenarios 2 to 3 demonstrate enhanced backing in the market mechanism by permitting elevated sellback rates.

These scenarios result in reduced LCOEs for various VRE–grid setups and enable greater energy generation proportions from VRE.

Scenario 4, conversely, raised the LCOE compared with other scenarios with market incentives, yet it stayed below the grid's LCOE, especially for systems including wind, PV, and the grid. The LCOEs for these system designs are between 3.2% and 15% less than the grid's LCOE. VRE generation without a sellback policy ranges from 30.1% to 38.2% in PV–grid configurations and reaches 49% in wind–solar–grid configurations. The results also indicate that higher grid sellback rates lead to an increase in VRE production, particularly from solar sources. In Scenario 4, wind electricity production can be enhanced, although systems that include wind and the grid show effects regarding greater wind energy results yet higher LCOEs in comparison with the grid. An additional key finding is that the LCOEs of wind–grid setups (without PV) are decreasing, becoming comparable with the grid's LCOE as the sellback rates rise.

The additional sensitivity and scenario analyses further support the main findings and suggest that the economic performance of hybrid renewable energy systems is more sensitive to policy and investment conditions than to future increases in the grid's electricity prices alone. PV-integrated systems are found to be more competitive with higher rates of electricity sellback, whereas increases in capital and installation costs have the most negative impact on LCOE. These results underscore the importance of enabling policies such as reasonable export-related compensation and investment incentives to improve the long-term economic viability and wider deployment of distributed renewable energy systems in regions with high solar resource potential and low wind potential.

The limitations of this study are the lack of energy storage, as it focuses on on-grid VRE systems, and a static electricity daytime tariff. Further scope for the research could include investigating more complex system arrangements by incorporating energy storage, dynamic tariffs, and microgrid configurations into the analysis, as well as more realistic system dynamics, including power quality, grid stability, and reliability challenges due to renewable energy's variability. Finally, although this research uses Indonesia as a case study, it provides insights into the technical and economic viability of improving the integration of VRE in small hotels located in other jurisdictions, given an environment with low wind.

Use of AI tools declaration

The authors declare they have not used AI tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Yusak Tanoto: Methodology, Writing—original draft, Review & editing, Formal analysis, validation; Yoel Christian Anggono: Writing—original draft, Data curation, Software, Visualization; Stephanus Antonius Ananda: Writing—review and editing, Project administration, Supervision.

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