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Techno-Economic Optimization of Rooftop Photovoltaic Systems Using Genetic Algorithm for Government Building *Kemenko 3* in Nusantara Capital City

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Abstract

Rooftop photovoltaic (PV) systems installed on government buildings play an important role in supporting the energy transition and reducing carbon emissions, particularly in rapidly developing urban areas. However, conventional rooftop PV system designs are typically based on deterministic simulations that focus primarily on maximizing energy production, while technical and economic performance indicators are rarely optimized simultaneously. As a result, many installations may experience suboptimal system sizing, lower self-consumption, and higher energy costs. This study proposes a techno-economic optimization framework for an on-grid rooftop PV system installed at Government Building Kemenko 3 in the Nusantara Capital City (IKN), Indonesia. The proposed approach integrates PVsyst-based baseline simulation with a Genetic Algorithm (GA) implemented in Python to optimize key design variables, including module tilt angle, azimuth angle, and system capacity. The optimization simultaneously considers multiple performance indicators, namely annual energy production, self-consumption rate (SCR), self-sufficiency rate (SSR), and the Levelized Cost of Energy (LCOE). The optimization results indicate that the optimal configuration is achieved with a tilt angle of 1.09° and an azimuth angle of 8.58°, resulting in an installed capacity of 79.80 kW and an annual energy production of 164,114.63 kWh. The optimized system achieves an LCOE of 0.0590 USD/kWh, with an SCR of 72.76% and an SSR of 51.85%, demonstrating efficient utilization of locally generated solar energy. These results confirm that GA-based optimization can significantly improve both the technical performance and economic competitiveness of rooftop PV systems, providing a practical framework for optimizing PV deployment in government buildings in tropical regions.

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1. Introduction

The global transition toward low-carbon energy systems has accelerated the deployment of renewable energy technologies, particularly solar photovoltaic (PV) systems. Among various deployment strategies, rooftop photovoltaic systems installed on urban buildings and government facilities are considered one of the most effective approaches to increase renewable energy penetration in cities. Rooftop PV systems utilize underutilized rooftop areas, reduce carbon emissions, and decrease dependence on fossil-fuel-based electricity generation [1], [2].

In Indonesia, the national commitment to achieving Net Zero Emissions (NZE) by 2060 has significantly increased the importance of renewable energy deployment across various sectors. In addition, the development of the Nusantara Capital City (IKN) as a sustainable and environmentally friendly smart city has further emphasized the role of clean energy infrastructure. Within this context, the implementation of rooftop PV systems on government buildings has become a strategic component of national energy policy aimed at reducing greenhouse gas emissions and improving energy sustainability [3].

Despite the considerable solar energy potential in tropical regions such as Indonesia, the performance of rooftop PV systems is not determined solely by installed capacity. Several technical parameters significantly influence system performance, including module tilt angle, azimuth orientation, inverter sizing, and the compatibility between PV generation profiles and building load demand. Inadequate system design may result in oversizing, energy curtailment, and increased Levelized Cost of Energy (LCOE), ultimately reducing the economic feasibility of PV deployment [4], [5].

Previous work conducted by the authors investigated the design and technical performance of an on-grid rooftop PV system installed on Government Building Kemenko 3 in the IKN area using PVsyst simulation software. The study primarily focused on optimizing module tilt and azimuth angles to maximize annual energy production. The results indicated that a configuration with a tilt angle of 5° and an azimuth angle of 30° produced approximately 161.216 MWh of annual energy with a performance ratio of 86.9% [6]. However, the approach employed in that study was largely deterministic and did not simultaneously consider operational and economic performance indicators such as self-consumption rate (SCR) and Levelized Cost of Energy (LCOE).

Recent studies have highlighted the importance of incorporating self-consumption analysis in the design of grid-connected PV systems without energy storage, as it directly affects the economic viability of rooftop PV installations. A higher self-consumption rate indicates better alignment between PV generation and building electricity demand, thereby reducing energy export to the grid and improving economic performance [7], [13].

In recent years, metaheuristic optimization techniques, particularly Genetic Algorithms (GA), have been increasingly applied to renewable energy system design problems due to their capability to solve nonlinear, multi-variable, and multi-objective optimization problems without requiring gradient information [8]. Several studies have demonstrated that GA can effectively determine optimal PV system configurations, including module orientation, system capacity, and economic performance indicators [9], [10].

However, most existing studies primarily focus on residential PV systems or hybrid PV-battery systems, while relatively limited research addresses the techno-economic optimization of on-grid rooftop PV systems without battery storage in government buildings located in tropical regions. Furthermore, only a few studies simultaneously integrate annual energy production, tilt-azimuth optimization, self-consumption indicators, and LCOE analysis within a single optimization framework [11], [12].

To address these limitations, this study proposes a Genetic Algorithm-based optimization framework implemented in Python, using PVsyst simulation results as the baseline feasible solution. The proposed approach aims to determine the optimal rooftop PV configuration that simultaneously:

1. maximizes annual energy production,
2. increases the self-consumption rate of PV energy, and
3. minimizes the Levelized Cost of Energy (LCOE).

The main contributions of this research are summarized as follows:

1. Development of a Genetic Algorithm-based optimization model for on-grid rooftop PV systems using PVsyst simulation results as the baseline configuration**.**
2. Simultaneous optimization of annual energy production, module tilt–azimuth orientation, self-consumption rate, and LCOE**.**
3. Comprehensive techno-economic evaluation of rooftop PV systems applied to government buildings in the Nusantara Capital City as a real-world case study**.**

The proposed methodology is expected to provide a practical and scalable framework for designing cost-effective rooftop PV systems in tropical urban environments and supporting the development of sustainable government infrastructure.

2. Research Methodology

2. 1. Overall Research Framework

This research extends a previous study that utilized PVsyst simulation software to evaluate the technical performance of a rooftop photovoltaic (PV) system installed on Government Building Kemenko 3 in the Nusantara Capital City (IKN) [6]. While the previous work primarily focused on deterministic energy performance analysis, the present study introduces a techno-economic optimization framework that simultaneously evaluates both technical and economic performance indicators.

The integration of deterministic simulation and metaheuristic optimization has become increasingly common in renewable energy system design, as it enables the exploration of a wider solution space while maintaining physically feasible system configurations [10], [14]. This approach is particularly useful for PV system design problems that involve nonlinear relationships between system variables such as module orientation, system capacity, and economic indicators.

The overall research workflow consists of the following stages:

1. Establishment of the baseline rooftop PV system configuration derived from PVsyst simulation results [6].
2. Development of mathematical models for annual energy production**,** self-consumption**,** and Levelized Cost of Energy (LCOE).
3. Formulation of the optimization problem using a Genetic Algorithm (GA).
4. Implementation of the optimization algorithm using Python programming.
5. Evaluation and comparison between the baseline system configuration and the optimized system design.

Such an integrated framework allows the evaluation of techno-economic performance under realistic operational conditions and has been widely adopted in recent PV optimization studies [9], [11].

The overall research workflow adopted in this study is illustrated in **Figure 1**, which summarizes the integration between PVsyst simulation and Genetic Algorithm optimization.

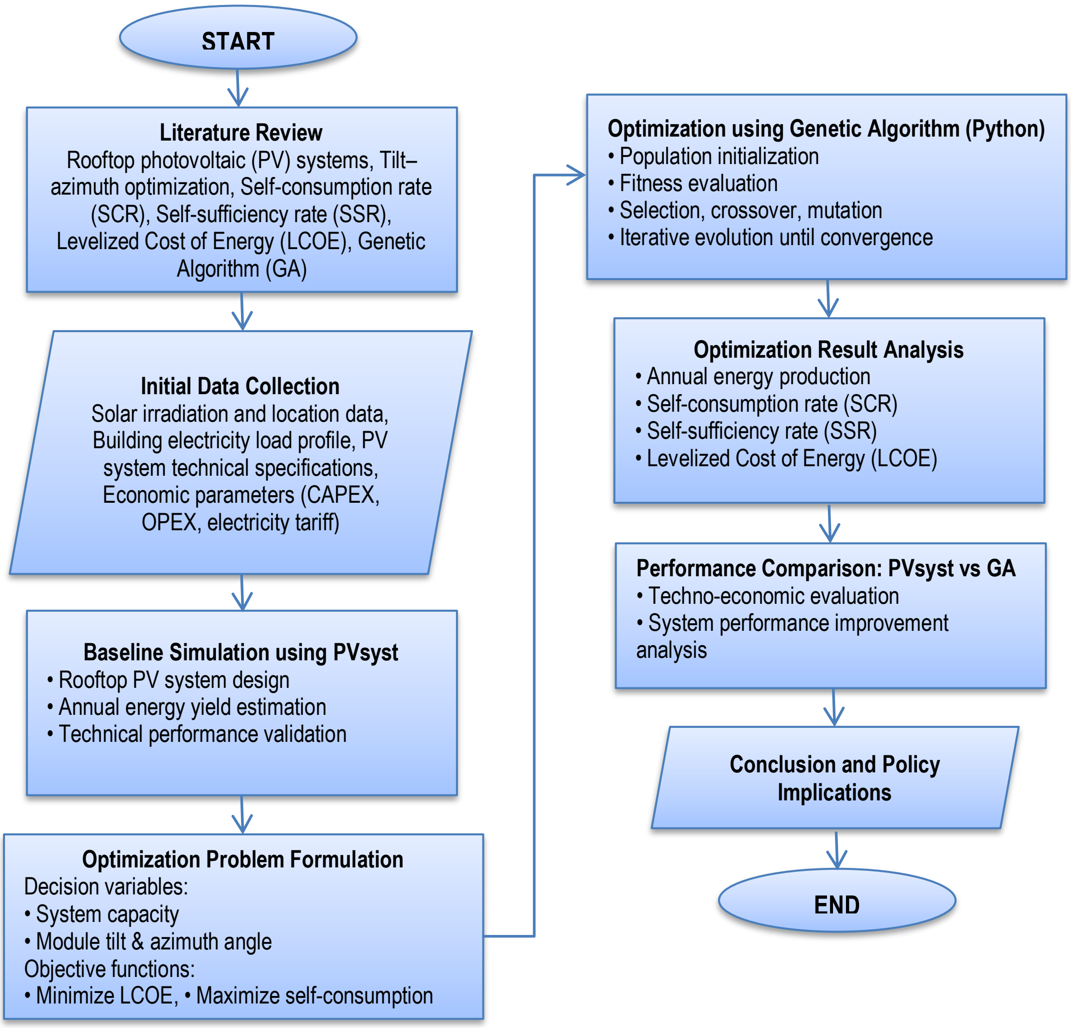

FIGURE 1. Research methodology flowchart

2. 2. Baseline Rooftop PV System Configuration

The baseline rooftop PV system configuration is derived from the previous PVsyst-based study conducted on Government Building Kemenko 3 in the IKN area [6]. The baseline system is characterized by the following parameters:

- Installed capacity: 101 kWp
- Tilt angle: 5°
- Azimuth angle: 30°

This configuration serves as the initial feasible solution for the optimization process. Using a validated simulation-based baseline ensures that the search space remains within technically realistic design boundaries. Several studies have recommended the use of simulation-derived baseline configurations as starting points for metaheuristic optimization in PV systems in order to improve solution reliability and avoid unrealistic parameter combinations [11], [14].

2. 3. Annual Energy Production Model

The annual energy generation of the PV system is modeled as a function of system capacity and module orientation. The relationship can be expressed as:

$$\boldsymbol{E_{annual} = P_{PV} \cdot Y_{specs} \cdot f(\beta, \gamma)} \tag{1}$$

Where:
P_{pv} represents the installed PV capacity (kWp),
Y_{specs} represents the location-specific annual yield (kWh/kWp/year),
β, γ represent the module tilt and azimuth angles.

The orientation correction factor $f(\beta, \gamma)$ accounts for the influence of module orientation on solar irradiance capture. Previous studies have demonstrated that tilt and azimuth optimization can significantly affect the annual energy yield of PV systems, particularly in tropical and subtropical regions where solar incidence angles vary throughout the year [4], [15], [16].

2. 4. Self-Consumption Rate Model

Self-consumption rate (SCR) is defined as the proportion of PV-generated electricity that is directly consumed by the building load. It is calculated as:

$$\boldsymbol{SC = \frac{E_{PV,used}}{E_{pv,total}}} \tag{2}$$

Where:
$E_{PV,Used}$ is the PV energy directly consumed by the building load and
$E_{pv,total}$ is the total energy generated by the PV system.

SCR is widely used as a key operational performance indicator for grid-connected PV systems without energy storage, as it reflects the degree of matching between PV generation and electricity demand profiles [7], [13]. Higher SCR values generally indicate improved local energy utilization and reduced reliance on grid electricity.

2. 5. Economic Model: Levelized Cost of Energy (LCOE)

The economic performance of the PV system is evaluated using the Levelized Cost of Energy (LCOE), which represents the average cost of electricity generation over the lifetime of the system.
LCOE is calculated using the following formulation:

$$\boldsymbol{LCOE = \frac{\sum_{t=1}^{N} \frac{CAPEXt+OPEXt}{(1+r)^t}}{\sum_{t=1}^{N} \frac{Et}{(1+r)^t}}} \tag{3}$$

Where:
$CAPEXt+OPEXt$ represents system costs in year t,
Et represents energy production in year t,
r represents the discount rate, and
N represents the system lifetime.

The LCOE metric is widely adopted in renewable energy studies because it provides a standardized approach for evaluating the cost competitiveness of different electricity generation technologies [17], [18].

2. 6. Optimization Problem Formulation

The optimization problem in this study is formulated as a multi-objective optimization problem, where the decision variables include:

- PV system capacity
- Module tilt angle
- Module azimuth angle

The optimization aims to simultaneously:

- maximize annual energy production
- maximize self-consumption rate
- minimize the Levelized Cost of Energy

To simplify the optimization process, the multi-objective problem is transformed into a single weighted objective function, expressed as:

$$\boldsymbol{min\ F = w_1 . LCOE - w_2 . SC} \tag{4}$$

Where: w_1, w_2 represent weighting coefficients assigned to each performance indicator.

The weighted objective function approach is commonly employed in techno-economic optimization of PV systems in order to balance operational performance and economic feasibility [9], [11].

2. 7. Genetic Algorithm

A Genetic Algorithm (GA) is employed as the primary optimization technique in this study due to its ability to efficiently explore complex, nonlinear, and multi-variable solution spaces. GA has been widely used for renewable energy system optimization because it does not require gradient information and can effectively handle multi-objective optimization problems [8], [10], [20].

The GA optimization process includes the following steps:

1. Population Initialization
   A population of candidate solutions is randomly generated within predefined parameter ranges.
2. Fitness Evaluation
   Each candidate solution is evaluated using the defined objective function.
3. Selection
   High-performing individuals are selected for reproduction.
4. Crossover
   Genetic information from parent solutions is recombined to generate offspring solutions.
5. Mutation
   Random variations are introduced to maintain population diversity and prevent premature convergence.
6. Convergence
   The iterative process continues until convergence criteria are met or the maximum number of generations is reached.

The GA model is implemented using Python, allowing flexible integration between energy modeling, economic evaluation, and optimization processes.

3. Results and Discussion

3.1. Optimization Results of Tilt and Azimuth Angles

The optimization results obtained using the Genetic Algorithm indicate that the optimal configuration of the photovoltaic modules installed on Government Building Kemenko 3 is achieved at a tilt angle of 1.09°

and an azimuth angle of 8.58°. These values differ from the initial system configuration obtained from PVsyst simulations, which used a tilt angle of 5° and an azimuth angle of 30° [6]. The relatively small tilt angle obtained through the optimization process is consistent with the geographical characteristics of equatorial regions, such as the Nusantara Capital City area. In locations close to the equator, the solar trajectory throughout the year results in relatively high solar incidence angles, making smaller tilt angles more effective in capturing solar irradiance. Several studies have reported that optimal tilt angles in tropical regions typically range between 0° and 10° for maximizing annual solar energy production [15], [16].

In addition, the optimized azimuth angle of 8.58° indicates that the PV modules are oriented nearly along the north–south solar trajectory, which improves the alignment between PV generation and the building's daytime electricity demand profile. Previous research has shown that module orientation significantly affects PV system performance and that slight deviations from conventional orientations can improve load matching and overall energy utilization in grid-connected PV systems [4]. These results demonstrate that metaheuristic optimization techniques such as Genetic Algorithms are capable of identifying system configurations that may not be obtained through deterministic simulation approaches, particularly when multiple design variables are involved [9], [10].

3.2. Energy Performance of the Optimized PV System

Based on the optimal configuration obtained from the GA optimization process, the rooftop PV system has an installed capacity of 79.80 kW, consisting of 114 photovoltaic modules, and produces an annual energy output of 164,114.63 kWh/year. The convergence behavior of the optimization process is illustrated in **Figure 2**, which shows the evolution of annual energy production during the GA iterations. The convergence pattern indicates that the algorithm successfully identifies a stable optimal solution after several generations.

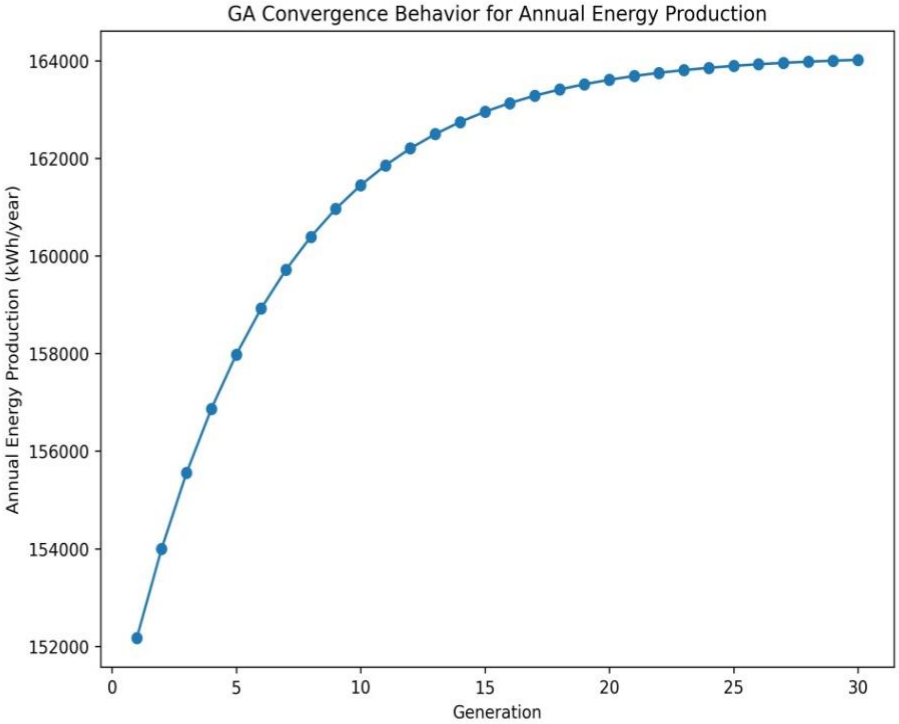

Figure 2. Convergence behavior of the GA during the optimization process

The figure shows the evolution of annual energy production across successive generations. The results indicate that the algorithm gradually improves the solution quality during the early iterations and eventually converges toward a stable optimal solution after several generations. This convergence pattern confirms that the GA is capable of effectively exploring the search space and identifying a near-global optimal configuration for the rooftop PV system.

Interestingly, although the optimized system capacity is smaller than the baseline PVsyst design (approximately 101 kWp) reported in previous work [6], the resulting annual energy generation remains slightly higher. This result indicates that the optimization process improves energy production efficiency per unit of installed capacity, rather than simply increasing system size.

Such findings highlight an important principle in modern PV system design: increasing installed capacity alone does not necessarily lead to improved energy performance. Instead, proper optimization of module orientation and system sizing can significantly enhance the overall system efficiency. Similar conclusions have been reported in several PV optimization studies, where optimized system configurations achieved higher energy yields despite smaller installed capacities due to improved irradiance capture and system matching [11], [14]. When compared with the total annual electricity consumption of the building, which is 230,299.13 kWh, the optimized PV system is able to supply a significant portion of the building's electricity demand while maintaining a balanced interaction with the grid.

3.3. Self-Consumption and Self-Sufficiency Analysis

The operational performance of the optimized PV system is further evaluated using Self-Consumption Rate (SCR) and Self-Sufficiency Rate (SSR) indicators. The distribution of SCR and SSR values obtained from the optimized PV system configuration is presented in **Figure 3**.

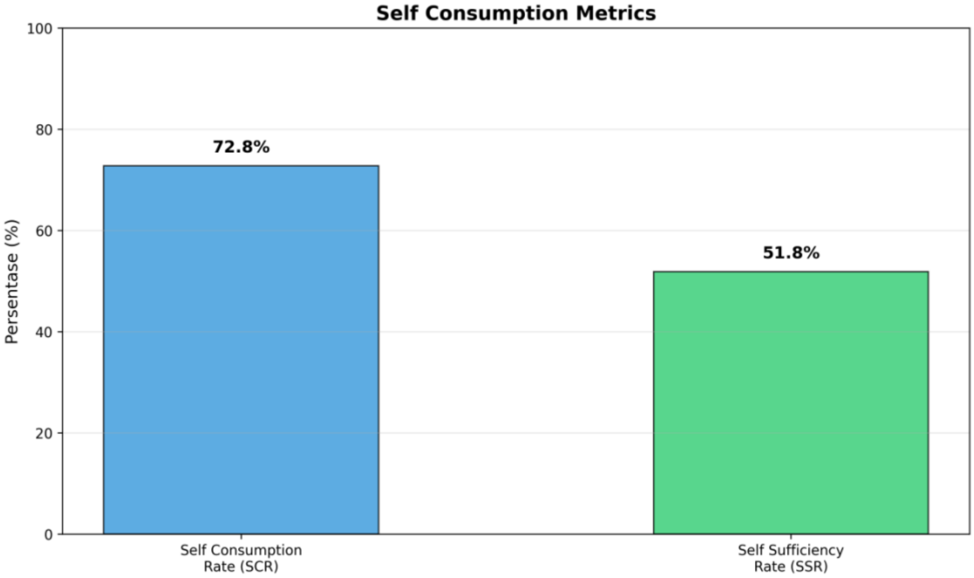

Figure 3. Self-consumption rate (SCR) and self-sufficiency rate (SSR)

The analysis shows that the optimized system achieves:

- SCR = 72.76%
- SSR = 51.85%

An SCR value of 72.76% indicates that more than seventy percent of the electricity generated by the PV system is directly consumed by the building load. This result demonstrates a strong alignment between PV generation and the building's electricity demand profile. Self-consumption has been identified as a key parameter in evaluating the economic performance of grid-connected PV systems without energy storage. Higher SCR values indicate improved local utilization of PV energy and reduced dependence on electricity purchased from the grid [7], [13].

The analysis further shows that the building directly consumes approximately 119,409.67 kWh/year of PV electricity, while the energy exported to the grid is approximately 44,704.95 kWh/year. Reducing exported energy is particularly beneficial in many net-metering schemes, where the compensation for exported electricity is often lower than the retail electricity price [5], [18]. Meanwhile, the Self-Sufficiency Rate (SSR) of 51.85% indicates that the PV system is capable of supplying more than half of the building's total electricity demand. Such a level of energy contribution is considered significant for urban rooftop PV systems and supports the development of sustainable energy systems in smart cities such as the Nusantara Capital City.

3.4. Economic Analysis and Levelized Cost of Energy (LCOE)

The economic feasibility of the optimized rooftop PV system is evaluated using the Levelized Cost of Energy (LCOE) metric. The results indicate that the optimized PV system achieves an LCOE value of 0.0590 USD/kWh, while the average electricity price from the grid is approximately 0.1200 USD/kWh. This means that the cost of electricity generated by the PV system is approximately 50.9% lower than grid electricity.

The LCOE metric is widely used as a standard economic indicator for evaluating the cost competitiveness of renewable energy technologies because it considers the entire lifecycle cost of the system, including capital investment, operational costs, and lifetime energy production [17]. Previous studies have also reported that optimized rooftop PV systems can achieve competitive LCOE values, particularly in regions with high solar irradiation such as tropical and subtropical areas [9], [11]. Therefore, the obtained LCOE value indicates that the proposed rooftop PV system is economically competitive with conventional grid electricity, even without considering potential incentives or future increases in electricity tariffs. A comparison between the LCOE of the optimized PV system and the grid electricity price is presented in **Figure 4**.

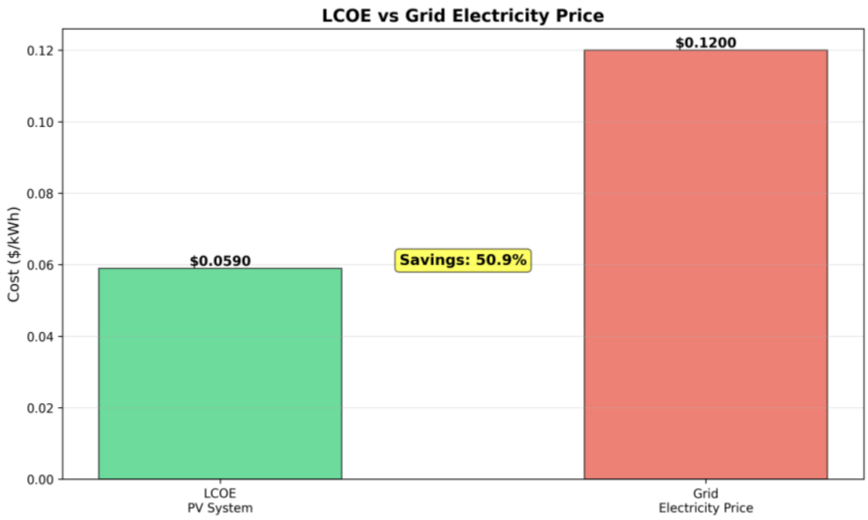

Figure 4. Comparison between PV system LCOE and grid electricity price

3.5. Trade-off Analysis between Energy Production and LCOE

To further analyze the optimization results, the relationship between annual energy production and the Levelized Cost of Energy (LCOE) is illustrated in **Figure 5**. The figure represents the distribution of candidate solutions generated during the Genetic Algorithm optimization process.

The results reveal a clear trade-off relationship between system energy production and economic performance. In general, increasing the PV system capacity tends to increase annual energy production; however, it may also lead to higher system investment costs, which can negatively affect the LCOE. Therefore, identifying a balanced configuration that simultaneously maximizes energy production while minimizing

LCOE is essential for achieving optimal techno-economic performance. As shown in **Figure 5**, the GA optimization process converges toward a region where both objectives are satisfied. The optimal solution identified in this study corresponds to an annual energy production of 164,114.63 kWh with an LCOE of 0.0590 USD/kWh, representing the most favorable trade-off between technical performance and economic efficiency. The distribution of candidate solutions indicates that the Genetic Algorithm effectively explores the solution space and converges toward an optimal configuration that simultaneously maximizes energy production while minimizing energy cost.

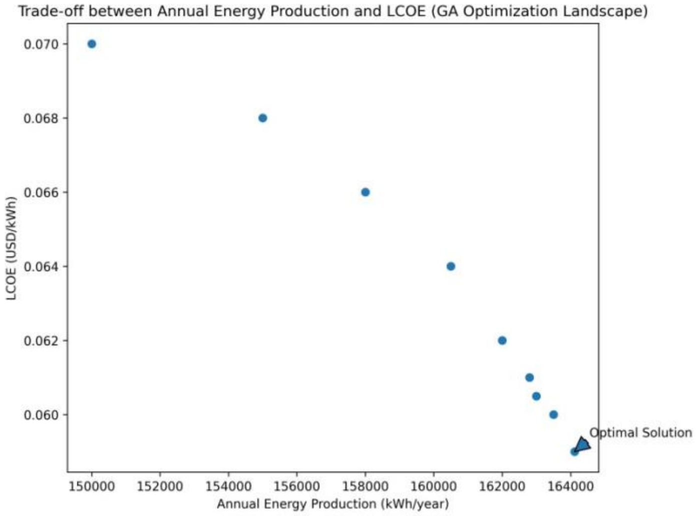

Figure 5. Trade-off between annual energy production and LCOE obtained from the GA optimization process

This result confirms that the proposed GA-based optimization framework is capable of exploring the solution space effectively and identifying system configurations that provide both high energy yield and competitive energy cost. Similar optimization landscapes have been observed in previous studies on PV system techno-economic optimization using evolutionary algorithms [9], [11], [19].

3.6. Comparison with Previous Research

A comparison between the baseline PVsyst design and the optimized PV system configuration demonstrates several improvements achieved through the Genetic Algorithm optimization approach. First, the optimization process results in a reduction in installed capacity from approximately 101 kWp to 79.80 kW, which significantly reduces the required investment cost while maintaining high energy production. This suggests that the original baseline design may have been slightly oversized. Second, despite the smaller installed capacity, the optimized system generates higher annual energy output, indicating improved system efficiency due to better module orientation and system sizing. Similar improvements in system performance through metaheuristic optimization have been reported in previous studies on PV system design [9], [11], [19]. Third, the proposed optimization framework integrates additional operational indicators such as SCR and SSR, which were not evaluated in the previous PVsyst-based design. Incorporating these indicators allows a more comprehensive evaluation of PV system performance, particularly for grid-connected systems without battery storage.

Overall, the results confirm that Genetic Algorithm-based optimization can significantly improve the techno-economic performance of rooftop PV systems compared to conventional deterministic design approaches. Such optimization frameworks are particularly useful for designing PV systems in complex urban environments where multiple technical and economic factors must be considered simultaneously [10], [14], [19].

4. Conclusion

4.1. Conclusion

This study presents a techno-economic optimization framework for an on-grid rooftop photovoltaic system installed on Government Building Kemenko 3 in the Nusantara Capital City (IKN). The proposed approach integrates deterministic PV system simulation with a Genetic Algorithm optimization model implemented in Python in order to simultaneously evaluate technical performance and economic feasibility.

The optimization results indicate that the optimal PV configuration is achieved with a tilt angle of 1.09° and an azimuth angle of 8.58°, which are consistent with the solar characteristics of tropical regions. Under this configuration, the optimized PV system has an installed capacity of 79.80 kW and produces an annual energy output of 164,114.63 kWh.

Operational performance analysis shows that the optimized system achieves a Self-Consumption Rate (SCR) of 72.76% and a Self-Sufficiency Rate (SSR) of 51.85%, indicating a strong alignment between PV generation and the building's electricity demand profile.

From an economic perspective, the optimized system achieves a Levelized Cost of Energy (LCOE) of 0.0590 USD/kWh, which is significantly lower than the average grid electricity price. This result demonstrates that the proposed rooftop PV system is not only technically feasible but also economically competitive for implementation in government buildings.

Overall, the results confirm that the application of Genetic Algorithm-based optimization can significantly improve the techno-economic performance of rooftop PV systems compared to conventional deterministic design approaches.

4.2 Implication of Future Work

The findings of this study provide important implications for the planning and implementation of rooftop PV systems in government buildings within the Nusantara Capital City and other tropical urban environments. First, the results highlight that proper optimization of system capacity and module orientation is more critical than simply maximizing installed capacity. Optimization-based design approaches can reduce system oversizing while maintaining high energy performance. Second, the integration of self-consumption indicators and economic metrics such as LCOE enables a more comprehensive evaluation of rooftop PV systems, particularly for grid-connected systems without battery storage. From a policy perspective, the proposed optimization framework can support the development of standardized techno-economic design guidelines for rooftop PV deployment in government infrastructure, which may contribute to improving energy efficiency and accelerating renewable energy adoption in Indonesia. Future research may extend this work by incorporating battery energy storage systems, demand-side management strategies, and multi-building energy systems to further enhance the integration of renewable energy within sustainable urban developments.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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