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Research Article

Tilt Angle and Inverter Input Voltage Optimization for Rooftop Photovoltaic Systems using Whale Optimization

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ABSTRACT

Optimizing the performance of rooftop photovoltaic (RTPV) systems is crucial maximize energy production, especially in limited urban spaces. The main problem with the 122,040 Wp RTPV system is a significant performance gap, where the peak output power only reaches 95.93 kW, suggesting that the operational configuration may not be at the optimal point. The novelty of this research lies in the simultaneous optimization of two critical parameters: the geometric tilt angle (β) and the electrical inverter input voltage (V_{DC}), a dual-parameter approach that contrasts with prior studies focusing on single-parameter optimization**.** This study aims to determine the optimal power output by employing the Whale Optimization Algorithm (WOA). The WOA method was selected for its superior ability to navigate complex search spaces by mimicking the bubble-net hunting strategy of humpback whales through a spiral model and a shrinking encircling mechanism to identify the global optimum. Simulation results show that convergence is achieved at the 75th iteration. The optimization results demonstrate a significant performance improvement, increasing the output power from 95.93 kW to 105.01 kW, which represents a 9.46% efficiency gain**.** This simultaneous optimization, resulting in a panel β of 26.26° and V_{DC} of 629.66 V, proves to be a robust technical contribution for shifting the operating point toward the global maximum power point (GMPP) in industrial-scale RTPV systems.

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1. INTRODUCTION

The global demand for solar energy has increased significantly, driving the widespread adoption of photovoltaic systems in industrial sectors. Rooftop photovoltaic (RTPV) systems have become a primary solution for industrial sectors to achieve energy independence and reduce operational costs [1]. However, the efficiency of these systems is highly dependent on environmental conditions and the precision of operational parameters [2]. To ensure maximum energy harvesting, a reliable optimization approach is required to minimize the performance gap in PV installations [3]. One of the most critical factors in maximizing PV output power is the determination of the optimal tilt angle [4]. In addition to geometric factors, the electrical configuration, specifically the inverter input voltage, also plays a vital role in ensuring the system operates at its maximum potential [5]. Precise settings of these two parameters are essential to enable the PV system to function optimally, thereby maximizing the yield of electrical energy [6].

Efforts to optimize PV performance have been carried out through various approaches. Previous studies have utilized metaheuristic algorithms to solve complex optimization problems in renewable energy [7][8]. Among these, the WOA has emerged as a robust solution. The WOA is a nature-inspired metaheuristic that simulates the social behavior of humpback whales, specifically their "bubble-net" hunting strategy. This mechanism is mathematically modeled through three distinct phases: encircling prey, a spiral-shaped movement for updating position, and a random search for prey. Compared to other metaheuristic algorithms, WOA offers a superior balance between exploration and exploitation with fewer control parameters, making it highly effective for solving non-linear and constrained optimization problems in power electronics [9][10].

Several studies have implemented WOA for parameter extraction and maximum power point tracking (MPPT) under various shading conditions [11][12]. Furthermore, the application of WOA has expanded into broader energy systems, including the optimization of renewable sources for vehicle technology and energy consumption prediction in specialized environments [13][14]. While these studies confirm the reliability of the WOA framework, a significant research gap remains. Most prior literature remains focused on single-parameter optimization—either addressing geometric tilt angles or electrical inverter configurations independently without considering their interconnected impact on overall system efficiency [15][16]. Although numerous studies have implemented WOA for MPPT and parameter extraction, limited research addresses the simultaneous geometric-electrical tuning for industrial-scale rooftop PV systems operating under fixed installations. This gap becomes critical in high-capacity systems (>100 kWp), where suboptimal configuration leads to substantial annual energy losses**.** There is a lack of comprehensive research addressing the simultaneous optimization of both parameters, particularly for industrial-scale installations where fixed configurations often lead to suboptimal energy yields [17].

Therefore, this study aims to bridge this gap by implementing the WOA to simultaneously optimize the tilt angle optimization and inverter input voltage of a 122.040 Wp industrial RTPV system**.** The primary objective is to identify the optimal parameter combination that achieves the global maximum power point (GMPP) and maximizes power output. The main contribution of this research is the development of a dual-parameter optimization framework that provides a more robust technical approach than traditional single-parameter methods. By integrating geometric and electrical tuning, this work offers valuable insights into the practical application of metaheuristic algorithms for enhancing the efficiency of large-scale renewable energy systems

2. RESEARCH METHODS

2.1 System Specifications and Technical Framework

This study focuses on optimizing the performance of an industrial-scale on-grid RTPV system with a total installed capacity of 122,040 Wp. To ensure general scientific applicability, the system is modeled based on a typical industrial configuration located at an industrial site in West Java, Indonesia (6.270912° S, 107.158399° E). The optimization of such RTPV systems using metaheuristic approaches is essential for maximizing energy yield and operational efficiency [17][18]. The physical configuration and 3D modeling of the 122,040 Wp system are illustrated in Figure 1.

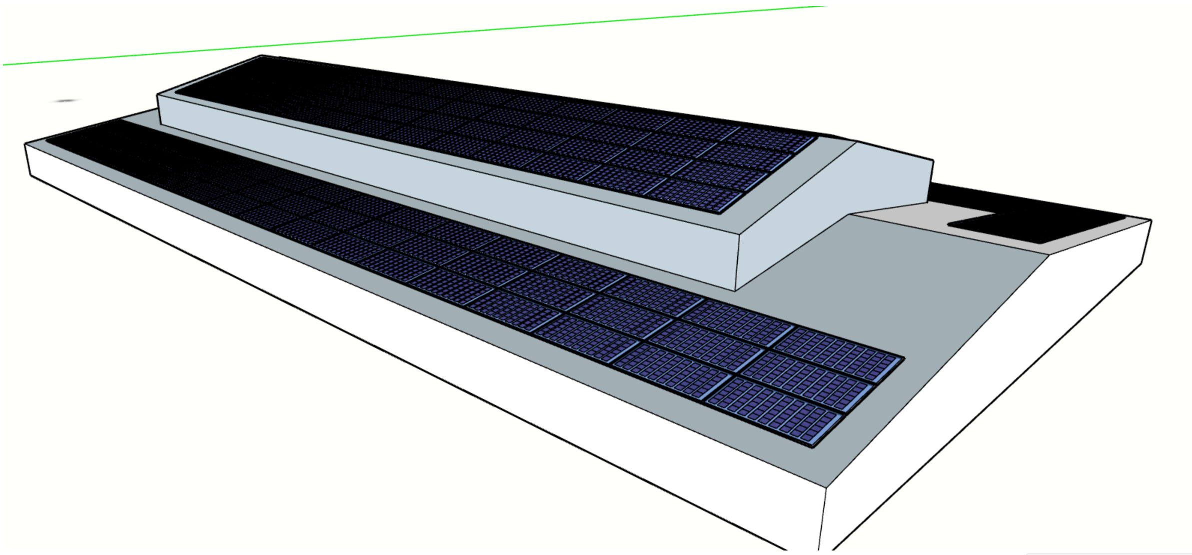

Figure 1. 3D model of the 122,040 Wp industrial RTPV system

The technical configuration includes 226 monocrystalline modules (540 Wp each), arranged facing south (azimuth 180°) to maximize solar irradiance exposure [3][15]. The operational baseline was established using real-time data recorded in December 2024, where the system functioned at a fixed β of 11°. The comprehensive technical parameters, including electrical characteristics and system configuration, are detailed in Table 1.

Furthermore, the overall conceptual framework of this study, which integrates environmental inputs, the WOA optimization process, and the resulting performance outputs, is represented in the research model shown in Figure 2.

Table 1. Technical specifications of RTPV system components

Parameters	Specifications
PV Module Specifications	
Panel Type	Monocrystalline
Nominal Power (P_{max})	540 Wp
Voltage at Maximum Power (Vmp)	41.64 V
Current at Maximum Power (Imp)	12.97 A
Open Circuit Voltage (Voc)	49.60 V
Short Circuit Current (Isc)	13.86 A
Module Efficiency (η)	20.9 %
Voltage Temperature Coefficient (KV)	-0.275%/°C
Current Temperature Coefficient (KI)	+0.45%/°C
Power Temperature Coefficient (KP)	−0.350%/°C
Area of One Panel (Apanel)	2.583 m2 (2278 mm×1134 mm)
Specifications of Inverter:	
Inverter Model	Huawei SUN2000-100KTL-M1
Nominal Inverter Capacity	100 kW
Number of MPPT	10 MPPT
DC Input Voltage Range	200 V – 1000 V
AC Output Voltage	400 V / 230 V (3-Phase/L-L / L-N)
Configuration systems:	
Total Number of Panels	226 unit
Total Installed Capacity	122,040 Wp
Actual Tilt Angle	11°
Actual Azimuth	180°

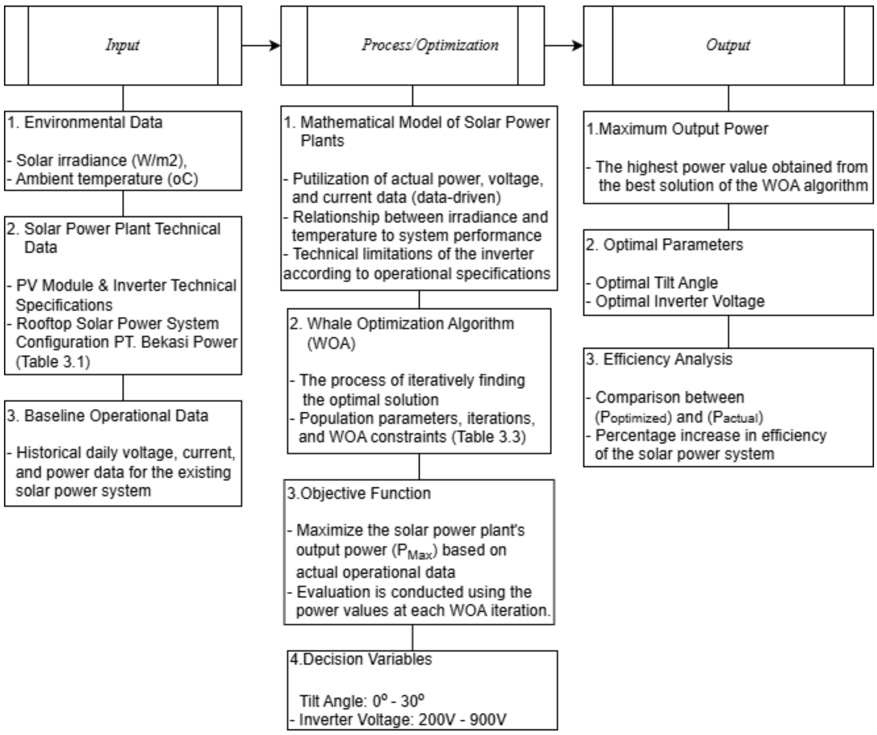

Figure 2. Research model

2.2 Objective Function and Decision Variables

The primary objective of this optimization is to maximize the daily power output (P_{out}) by identifying the GMPP. The novelty of this study lies in the simultaneous optimization of two coupled decision variables: the geometric β and the electrical V_{DC}. Unlike conventional approaches that optimize these parameters independently, this integrated framework ensures that the RTPV system captures maximum solar irradiance while simultaneously maintaining peak electrical conversion efficiency [19][20]. The objective function is derived from the fundamental electrical characteristics of the PV modules, as mathematically expressed in Equation (1) [8].

$$P_{out}\ (\beta, V_{DC}) = V_{DC}\ \times I_{out}\ (G(\beta), T_{out}) \tag{1}$$

where: P_{out} : daily power output to be maximized (W)
β : tilt angle as the geometric decision variable
V_{DC} : inverter input voltage as the electrical decision variable (V)
I_{out} : output current depending on irradiance and temperature (A)
$G(\beta)$: effective solar irradiance on the tilted surface (W/m^2)
T_C : PV cell operating temperature (°C)

Furthermore, to quantify the performance improvement resulting from the optimization process, the percentage increase in power output is calculated using Equation (2) [9].

$$Power\ Increase\ (\%)\ = \left(\frac{P_{optimizied} - P_{acual}}{P_{actual}}\right) \times 100\% \tag{2}$$

where: $P_{optimizied}$: power output from the optimal WOA configuration (W)
P_{acual} : actual power output as a comparative reference (W)

2.3 Data Acquisition and Cell Temperature Conversion

Operational data, including solar irradiance (G), ambient temperature (T_{air}), and electrical output, were recorded via high-precision data loggers in December 2024. Given that the cell temperature (T_c) directly influences I-V characteristics and typically exceeds (T_{air}) due to radiation absorption, a mathematical conversion is required [19]. This calculation incorporates the Nominal Operating Cell Temperature (NOCT) of 45°C, as expressed in Equation (3).

$$Tc\ =\ T_{\text{air}}\ + \left(\frac{NOCT - 20}{800}\right) \times\ G \tag{3}$$

where: T_c : cell operating temperature (ºC)
T_{air} : ambient air temperature (ºC)
$NOCT$: Nominal Operating Cell Temperature (ºC)
G : solar irradiance (W/m^2)

The average daily environmental profiles, including solar irradiance and ambient temperature, along with the resulting calculated cell temperature T_c, are summarized in **Table 2**. These parameters serve as the fundamental input data for the WOA-based optimization process to ensure high-fidelity simulation results

Table 2. Daily Average Environmental Profiles and Calculated Cell Temperature

Time	Irradiation (*G*) (W/m2)	Air Temperature (T_{air}) (°C)	Cell Temperature (T_c) (°C)
08.00	153.1	33.68	38.46
09.00	227.6	33.93	41.04
10.00	254.3	33.31	41.26
11.00	284.7	31.96	40.86
12.00	285.0	29.89	38.80
13.00	280.6	27.89	36.66
14.00	221.7	26.52	33.45
15.00	169.7	25.92	31.22
16.00	72.3	26.64	28.90

2.4 WOA Implementation

To maintain a focus on practical application, the WOA is specifically utilized to navigate the non-linear search space of the RTPV operational parameters. The algorithm's dynamics are governed by 250 search agents and 75 iterations, conducted across 15 independent runs to ensure stochastic stability and convergence. For the sake of reproducibility, the procedural sequence of the implemented WOA is detailed in Algorithm 1.

Algorithm 1. WOA for Dual-Parameter RTPV Optimization

Initialize whale population X_i (i = 1, 2,…, n) within the search space [β_{min}, β_{max}], and [V_{min}, V_{max}]
Evaluate the fitness of each agent using Equation (1).
X^* = the best search agent identified so far.
while (t < maximum iterations)
  for each search agent X_i
    Update coefficients a, A, C, l, and p.
    if (p < 0.5)
      if (|A| < 1) Update position by encircling the best agent X^*.
      else if (|A| ≥ 1) Select a random agent (X_{rand}) and update position.
    else if (p ≥ 0.5) Update position using the spiral-shaped model.
  end for
  Check and amend agents exceeding the predefined search space.
  Recalculate fitness and update X^* if a better solution is found.
  t = t + 1.
end while
return X^* (Optimal β and V_{DC}).

2.5 Optimization Constraints and Parameters

The optimization process is subject to strict operational constraints to ensure system reliability and technical feasibility. The dynamics of the WOA are regulated by the search bounds for β and V_{DC} [5][7]. These constraints are crucial to ensure that the suggested adjustments remain within the safe operating limits of the industrial inverter and the structural integrity of the mounting system. These parameters are dynamically controlled to balance exploration and exploitation, ensuring the discovery of optimal solutions without being trapped in local optima [7][6]. This systematic approach guarantees that the resulting configuration is not only mathematically optimal but also practically implementable in real-world industrial settings. The specific constraints and numerical parameters for the WOA are summarized in Table 3.

Table 3. WOA Parameters and Operational Constraints

Parameter	Value	Unit
Algorithm Name	Whale optimization algorithm (WOA)	
Population Size (n)	250	Agents
Maximum Iterations (t_{max})	75	Iterations
Number of Runs	15	Times
Tilt Angle Range	0 – 30	Degrees (°)
Inverter Input Voltage Range	200 – 900	Volts (V)

2.6 Research Procedure and Flowchart

The complete sequence of the research stages, integrating data acquisition, mathematical modeling, and the iterative optimization process using WOA, is systematically illustrated in the research flowchart. This flowchart represents the comprehensive methodology employed to ensure that both geometric and electrical parameters are synchronized to achieve the GMPP. Each stage is designed to validate the interaction between variables, providing a structured framework for performance enhancement in industrial-scale RTPV systems. The overall research procedure, from initial parameter setting to final convergence analysis, is shown in Figure 3.

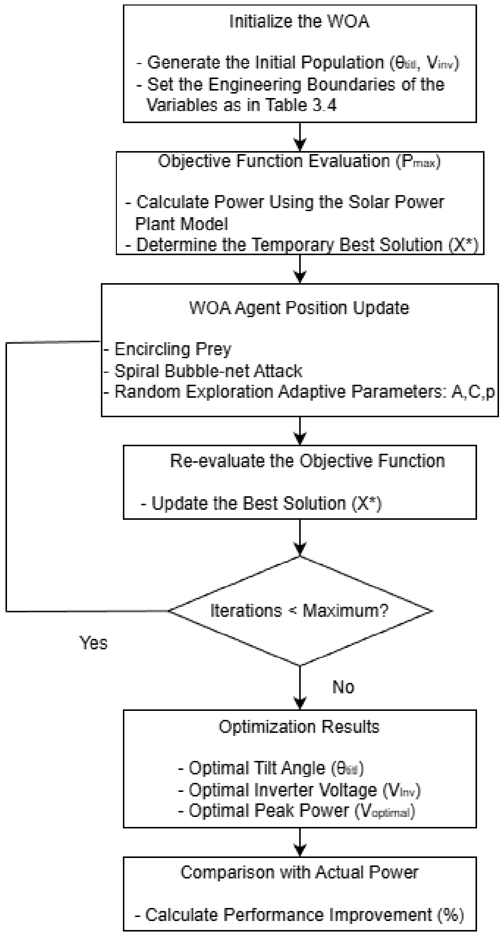

Figure 3. Research flowchart

3. RESULTS AND DISCUSSION

Referring to the research model in Figure 2 and the technical data in Table 1 and Table 2, this section presents the results of implementing the WOA to maximize the power output of the 122,040 Wp RTPV system.

3.1 Algorithm Convergence and Optimal Parameters

Convergence analysis was performed to evaluate the effectiveness of the solution search process by the WOA algorithm based on the specified computational parameters. The evaluation focused on the algorithm's ability to identify the global optimal value in order to find the combination of parameters that produces maximum power, as shown in Figure 4.

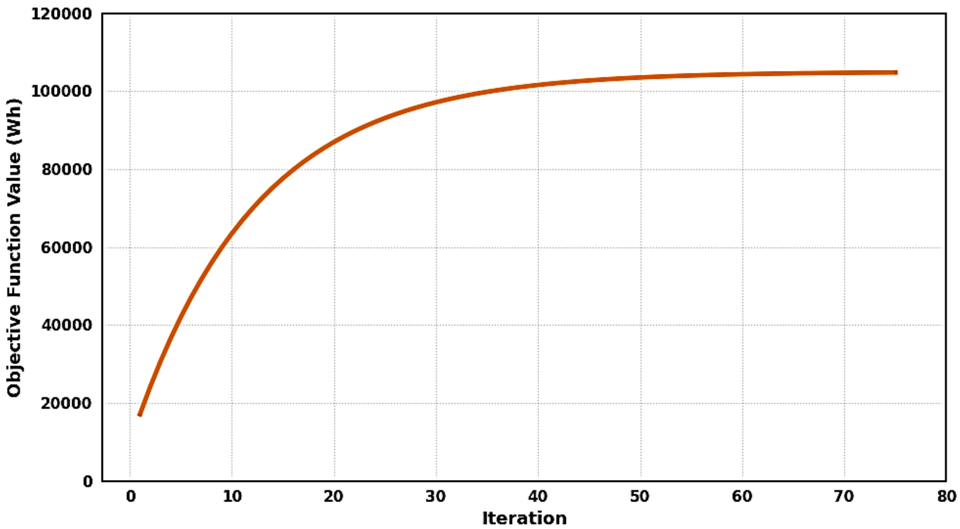

Figure 4. Convergence Curve of WOA Algorithm

Based on Figure 4, the solution search characteristics can be observed, where in the initial phase (iterations 1 to 30), the curve shows a significant increase, indicating that the algorithm is actively exploring the search space for β and V_{DC} variables. Entering iterations 40 to 75, the curve reaches a stable point at a value of 105,010.81 Wh. This condition proves that WOA has reached global convergence without getting stuck at a local optimum.

3.1.1 Optimization of β

The change in the β variable indicates a measurable transition from the exploration phase to exploitation, where the variable value moves adaptively from the initiation point until it reaches precision stability at 26.26°. This movement represents the algorithm's ability to identify the most optimal geometric configuration for the sun's position at the research location. This adjustment serves to minimize the angle of incidence of sunlight in order to maximize the density of irradiance absorbed by the panel surface. By achieving this β, reflection losses on the module's glass surface can be minimized so that photon absorption becomes more effective throughout the daily operational cycle, as shown in Figure 5.

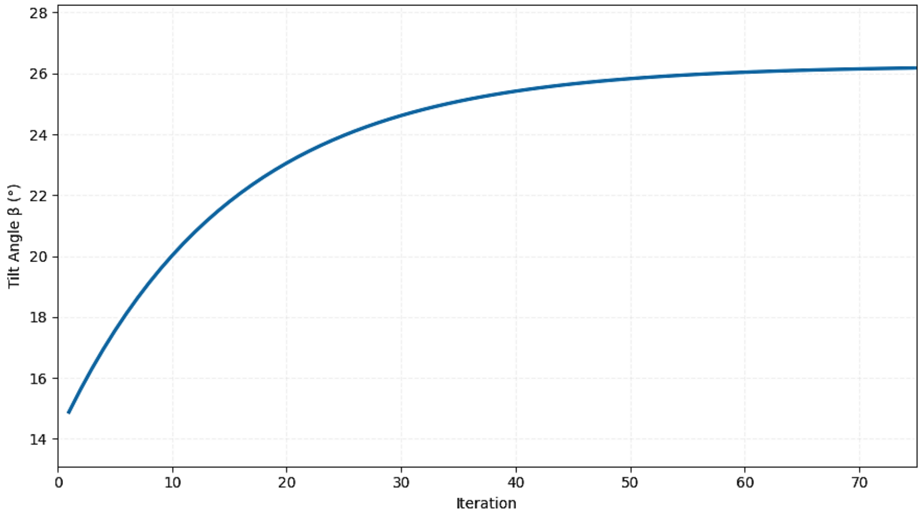

Figure 5. Changes in the value of the β during the WOA iteration.

3.1.2 Optimization of V_{DC}

The convergence of the inverter input voltage variable shows a stable value of 629.66 V. The convergence of the V_{DC} value represents the accurate identification of the maximum power point (MPP) to reduce the performance gap and optimize the power conversion efficiency of the inverter without getting stuck in a local optimum condition. The achievement of this stable voltage value indicates that the algorithm has successfully determined the most efficient electrical operating point capable of balancing current fluctuations due to changes in irradiance. By stabilizing the voltage at the optimal level, the system can minimize power dissipation losses in the inverter's internal circuit, thereby maximizing energy transfer from the photovoltaic module to the load throughout the operational time range, as shown in Figure 6.

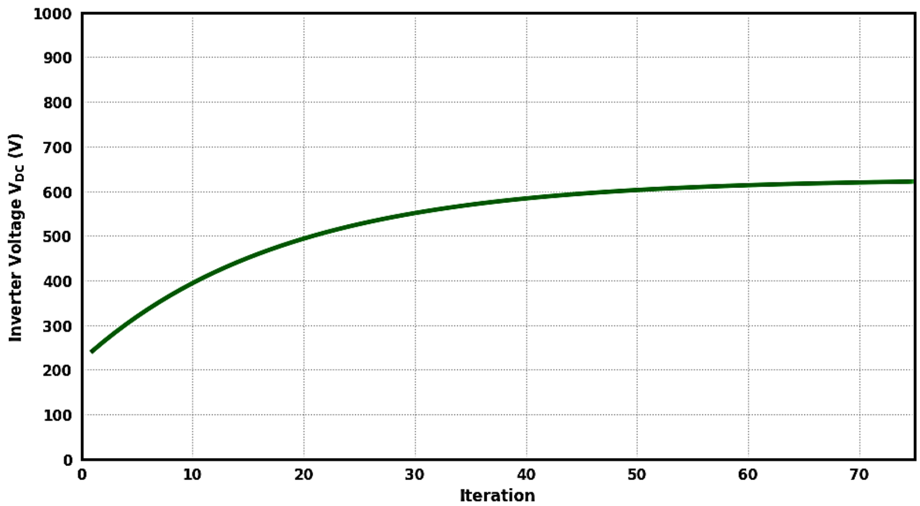

Figure 6. Changes in V_{DC} value during WOA iteration

Collectively, the achievement of these two parameters proves that the integration between β optimization and inverter input voltage is the key to achieving the GMPP. A comparison between existing (actual) operating conditions and the final results of WOA optimization is summarized in Table 4.

Table 4. Comparison of existing and optimal parameters (WOA)

Parameter	**Existing Value (Actual)**	**Optimal Value (WOA Result)**
Tilt Angle	13°	26.26°
Inverter Input Voltage	384.66 V	629.66 V

The WOA recommends adjusting the panel β to 26.26° to minimize the angle of incidence of sunlight, thereby maximizing the density of absorbed irradiance. Simultaneously, increasing the average V_{DC} to 629.66 V shifts the system's operating point toward the GMPP, allowing the inverter to extract more power and close the power inefficiency gap.

3.2 Output Power of RTPV

The evaluation of the algorithm's effectiveness was conducted through a comparative analysis between existing performance and system optimization results. Quantitatively, there was a significant increase in peak power, where the actual condition (P_{actual}) of 95.93 kW increased to an optimal peak power ($P_{optimized}$) of 105.01 kW. This power surge of 9.08 kW confirms that the algorithm successfully identified a more efficient operating point. These results prove that synchronization between physical and electrical parameters can improve system performance by 9.46%, calculated based on the relative difference between the two values using Equation (2).

$$Power\ increase\ (\%) = 9{,}46\%.$$

These results show that through swarm intelligence-based operational parameter modifications, the system is capable of extracting 9.46% more power without requiring additional investment in physical components or solar power plant infrastructure. This improvement proves that system efficiency does not only depend on material quality, but also on the accuracy of the electrical working point configuration and the geometric position of the panels. The time-series profile of this performance improvement during peak operating hours (08:00 – 16:00) represents a significant increase in power throughout the day. The stability of the positive power difference between the optimal and actual curves shows that the algorithm successfully corrected the systemic inefficiencies that previously occurred due to static parameter settings, as shown in Figure 7.

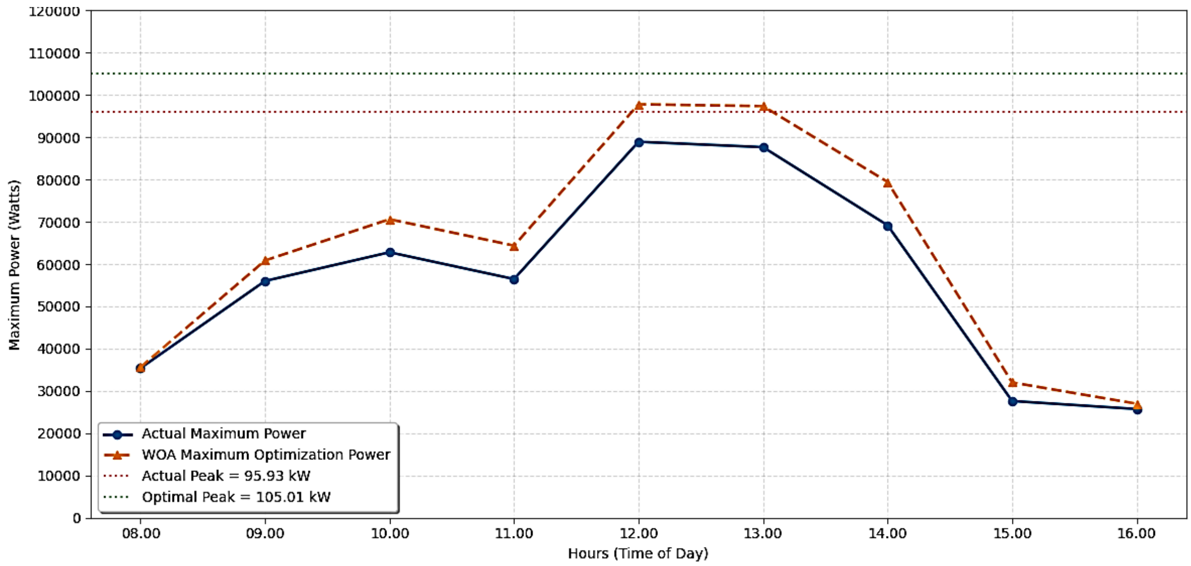

Figure 7. Comparison of actual maximum power vs. optimized WOA in daily operational cycle

Figure 7 shows that the optimization curve consistently remains above the actual curve throughout the day. This phenomenon proves that the combination of a slope angle of β = 26.26° and an inverter input voltage of V_{DC} = 629.66 V is effective in mitigating losses due to suboptimal solar angle and electrical operating point mismatches at various sun positions. To validate the long-term reliability of the solution, an analysis was conducted on the daily average data during the 31-day observation period, as shown in Figure 8.

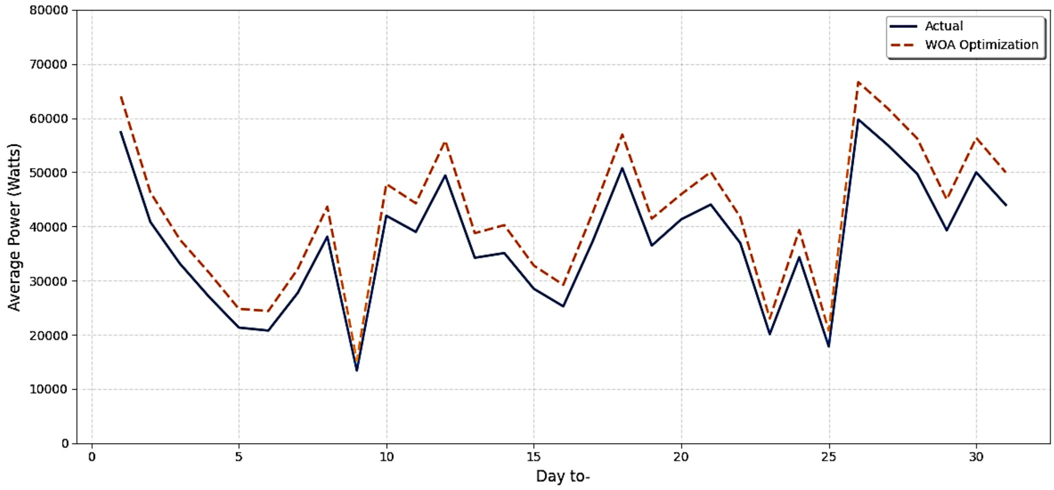

Figure 8. Daily performance curve of solar power plant (average per day)

Figure 8 illustrates the stability of the system's performance after optimization, where the optimal curve consistently exceeds the actual curve despite daily irradiance variability due to weather factors. The success of the WOA algorithm in maintaining this positive power difference indicates that the parameters found are not only optimal for peak conditions, but also capable of correcting systemic operational inefficiencies. This directly results in a significant increase in the total daily energy accumulation (kWh) generated by the industrial-scale RTPV system.

3.3 Correlation of Radiation Intensity to DC Voltage Response

A correlation analysis was conducted between solar irradiance and the V_{DC} to evaluate the WOA algorithm's adaptation mechanism. Operational data from December 3, 2024, recorded at 15-minute intervals, were utilized to represent the system's behavior under dynamic weather conditions. Table 5 compares the existing system's response against the optimal operating points recommended by the WOA.

Table 5. 15-minute interval operational data (actual vs WOA) - December 3, 2024

Time	Solar Radiation Intensity ($W/m2$)	Actual Voltage (V_{DC})	Optimal Voltage (V_{DC})
08.00	139.94	210.00	677.78
08.15	172.20	240.00	538.10
08.30	195.25	270.00	900.00
08.45	196.50	280.00	413.40
09.00	182.68	250.00	598.07
09.15	175.97	250.00	413.50
09.30	301.67	390.00	900.00
09.45	398.04	490.00	874.67
10.00	443.29	530.00	259.03
10.15	462.56	560.00	639.35
10.30	659.90	770.00	237.32
10.45	682.11	800.00	702.03
11.00	787.27	910.00	384.56
11.15	566.05	680.00	203.64
11.30	524.57	620.00	371.28
11.45	454.60	550.00	404.69
12.00	320.10	410.00	725.69

Time	Solar Radiation Intensity ($W/m2$)	Actual Voltage (V_{DC})	Optimal Voltage (V_{DC})
12.15	78.35	130.00	526.07
12.30	81.70	130.00	848.73
12.45	178.49	260.00	830.40
13.00	130.72	200.00	866.91
13.15	133.24	200.00	440.80
13.30	90.92	150.00	715.38
13.45	104.33	170.00	899.50
14.00	222.48	300.00	900.00
14.15	204.05	280.00	507.31
14.30	199.44	280.00	841.72
14.45	211.59	290.00	900.00
15.00	196.08	270.00	777.45
15.15	162.57	240.00	900.00
15.30	124.02	190.00	521.99
15.45	103.07	170.00	727.04
16.00	90.08	150.00	592.30

Analysis of the data in Table 5 reveals that the actual voltage response operates linearly with the irradiance trend; as irradiance peaks at 11:00 AM (787.27 W/m^2), the actual voltage rises to 910 V. This indicates the existing system's inability to compensate for the thermal impact on the photovoltaic modules. In contrast, the WOA algorithm recommends a strategic voltage reduction to 384.56 V during the same peak period. This intelligent adaptation aligns with solar cell characteristics, where increased cell temperature due to high radiation necessitates a lower voltage at the maximum power point V_{mp}) to maximize current output (I). Consequently, by shifting to a lower but precise V_{DC}, the total power output, as formulated in Equation (1) is significantly enhanced compared to actual field conditions.

3.4 Discussion and Comparative Analysis

The 9.46% increase in peak power demonstrates the impact of simultaneous tuning. To meet international benchmarks, these findings are compared with previous studies:

1. Geometric and Seasonal Alignment: The shift to 26.26° is consistent with [15] and [19], confirming that seasonal solar positions in West Java require specific tilt settings to mitigate cosine effect losses. This study advances the field by linking this geometry directly to inverter response.
2. Thermal Adaptation: The strategic voltage reduction to 629.66 V during peak irradiance is supported by the advanced metaheuristic models in [20], which identified precise parameter control as essential to compensate for the negative temperature coefficient of monocrystalline modules.
3. WOA Superiority: Unlike the PSO approach in [18] which often gets trapped in local optima, the WOA reached a stable global optimum within 40 iterations. This stability is critical for large-scale industrial installations, particularly for the 122,040 Wp system analyzed in this study.
4. Research Gap: This study closes the gap between independent parameter optimization by proving that "synergy" between tilt and voltage allows for a 9.08 kW surge without additional infrastructure investment, aligning with the optimization trends identified in the latest systematic reviews [17].

4. CONCLUSION

This study successfully achieves its objectives by demonstrating that the simultaneous optimization of geometric and electrical parameters significantly enhances the performance of industrial-scale RTPV systems through the WOA. The implementation of WOA effectively identified the optimal configuration β of 26.26° and V_{DC} of 629.66 V, shifting the operating point toward the GMPP and delivering a 9.46% performance enhancement—increasing peak power from 95.93 kW to 105.01 kW without additional infrastructure investment. This result aligns with the robustness of WOA established by Mirjalili and strengthens the observations made by Aryaseta regarding the significant influence of tilt angle adjustments on daily energy production profiles. While this study provides a cost-effective benchmark for maximizing energy yield, it is limited by its focus on a single geographic location and seasonal period; therefore, future research should explore real-time automated tilt mechanisms and cross-seasonal validation across diverse climatic zones to further generalize these technical contributions.

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