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Power Effectiveness Factor: A Method for Evaluating Photovoltaic Enhancement Techniques

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Abstract

Photovoltaic (PV) module enhancers, such as coolers and reflectors, are advanced technologies aimed at improving PV performance. The conventional approach for selecting the optimal PV enhancer relies on the observation of the highest power. While effective in comparing different enhancer designs, this method does not determine the maximum performance that the PV enhancer can achieve. To address this limitation, a new methodology is introduced that overcomes this drawback. It relies on three essential parameters: the net power gain with an enhancer, the power output of a PV module without an enhancer, and the maximum power of a PV module under standard test conditions. The impact of each parameter on the proposed method is analyzed, and enhancers are classified based on the method's output. Maximum or minimum performance is observed when the method's value is either in unity with or matches the ratio of a PV module's power output (without an enhancer) to its maximum power under standard conditions. To validate this approach in practical applications, experimental data from previous studies are examined. The results confirm that this technique can be applied for real-world cases and can effectively categorize PV enhancers, offering valuable insights for researchers, designers, and manufacturers.

Keywords: photovoltaic module; cooler; enhancer; power; assessment; performance; cooler; reflector

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1. Introduction

For hundreds of years, sunlight has served as a fundamental energy source for humanity, playing a crucial role in everyday life. Historically, solar energy was utilized to provide warmth and to preserve food by drying items such as fruits, grains, and meat. Over time, scientific advancements have paved the way for modern solar technologies that can generate both heat and electricity [1]. Among the most impactful developments is the photovoltaic (PV) module, which enables the direct conversion of sunlight into electrical energy [2,3].

In recent decades, global deployment of PV systems has increased significantly. For example, in 2010, global PV electricity production stood at 32.20 terawatt-hours (TWh), rising dramatically to 1002.90 TWh by 2021—nearly a 30-fold increase. This rapid growth has motivated ongoing research into methods for enhancing PV efficiency, including the integration of cooling devices and reflectors. The selection of an appropriate enhancement strategy depends primarily on climatic conditions. In hot and sunny climates, cooling

technologies are especially valuable for reducing PV temperatures through improved heat dissipation, typically via fluid circulation [4]. This thermal regulation directly contributes to improved PV output performance [5].

Numerous cooling strategies have been explored, spanning passive and active approaches. These systems use air, liquid media, or phase-change materials (PCMs) to maintain stable operating temperatures. An innovative enhancement involved a series-configured photovoltaic thermal (PVT) collector system designed to improve both thermal and electrical output [6]. Several nanofluid compositions were examined—including hybrid formulations like multi-walled carbon nanotube–silicon carbide and graphene–aluminum oxide. Among these, the carbon–silicon carbide hybrid nanofluid delivered the best results, reaching thermal and electrical efficiencies of 56.55% and 13.85%, respectively.

In another study, a 150 W PVT system was assessed using varied structural configurations to enhance thermal performance [7]. A comparative analysis focused on systems with longitudinal fins and inclined baffles versus setups with plain ducts. Using computational fluid dynamics (CFD), researchers determined that fins and baffles enhanced thermal efficiency by 12–18% compared to the plain configuration. Furthermore, a heat pump-integrated PVT model was experimentally validated [8], with optimization efforts aimed at maximizing heat dissipation. Marco and Renato [9] introduced a dual-source heat pump PVT system that improved ground regeneration during summer and maintained high electrical efficiency. Strategic separation of the heat sources and storage tanks added flexibility to the overall system design. Another experiment involved a glass-covered PV module connected to evaporator coils within a heat pump PVT system [10]. Evaluation using both empirical data and a validated numerical model under clear sky conditions revealed a 15.20% gain in electrical efficiency compared to systems lacking a glass cover.

On the other hand, solar reflectors are more advantageous in cooler regions with lower irradiance. Since their inception in 1958, reflectors have aimed to increase the incident solar energy captured by the PV surface, enhancing system efficiency [11]. Several experimental investigations have examined how the reflector design and material affect PV output [12], showing performance gains of up to 60%. For instance, a system with an aluminum sheet reflector showed a 15% boost in electrical output [13].

Further studies on V-trough concentrator systems demonstrated substantial power gains. One numerical and field-based analysis recorded a 31.20% increase in power under outdoor conditions [14], while another observed up to a 48% rise in output using similar setups [15]. Integrating both cooling mechanisms and reflectors into a single PV system led to a 10.68% performance improvement and offered an estimated payback period of 4.2 years [16].

A computational investigation into the impact of tilt angles on aluminum sheet reflectors revealed that system performance improved with a higher tilt, peaking at 19% efficiency when set at 75° [17]. The introduction of a curved reflector model yielded a 61% increase in collected solar energy per unit area [18]. Another integrated study, combining theoretical and experimental techniques, found that adding both a flat reflector and a cooling unit led to a 36% efficiency gain [19]. Additionally, a three-dimensional stainless-steel reflector model was developed, achieving a 34.16% improvement in PV efficiency [20]. Commonly, PV enhancers are constructed using high-conductivity materials like aluminum, copper, and stainless steel to aid in thermal management. However, the lifespan and resilience of these materials are influenced by local environmental conditions [21].

To illustrate performance differences, consider three PV coolers—Designs A, B, and C—tested under consistent conditions using the same PV module. Operating factors such as irradiance, ambient temperature, and airflow were controlled. The respective power outputs for these coolers were 2 W, 3 W, and 4 W, as presented in Table 1.

Table 1. PV cooler designs with different output power amounts.

PV Cooler Design	Power Output, W
Design A	2
Design B	3
Design C	4

From Table 1, it is evident by observation that Design C outperforms Design A and Design B, as it achieves the highest power output of 4 W. Yet a key question emerges: Is it possible for another PV cooler to outperform Design C, or does it already represent the peak of achievable efficiency? Identifying the most powerful PV cooler remains a complex task. Researchers aim to uncover the maximum potential of PV coolers to inform the development of highly efficient designs. However, traditional observation methods fall short in answering this crucial question, as they cannot confirm whether the current top performer is genuinely optimal or if further enhancements are still attainable.

Traditional evaluation approaches for PV enhancers often rely on either absolute power gain or efficiency improvement, assessed in isolation. While these methods provide partial insight, they frequently overlook the normalized performance potential of the PV module and fail to capture the combined effect of enhancement under real operating conditions. In contrast, the proposed Performance Effectiveness Factor (F_{PE}) offers a fundamentally different perspective by integrating the power outputs from both the enhanced and reference PV systems and normalizing them against the PV's rated capacity under standard test conditions (STCs). This allows for a more holistic and standardized comparison of performance gains, ensuring that enhancements are evaluated not only by their technical contribution but also by how close the system approaches or how much it surpasses its optimal rated performance.

The Present Study's Motivagtion

This research presents a new method for assessing photovoltaic (PV) enhancer performance by linking the module's power output—both with and without enhancement—to its rated output under standard test conditions (STCs). This correlation helps identify the upper limit of performance that a PV enhancer can achieve. To verify the effectiveness of this approach, data from earlier experimental investigations were utilized, confirming its applicability in practical scenarios. The proposed method offers valuable insights for professionals engaged in the development and optimization of PV enhancement systems, including researchers, engineers, and manufacturers.

The structure of the paper is divided into four main sections. Section 1 introduces the study, highlighting various PV enhancement techniques, reviewing the relevant literature, and outlining the research rationale. Section 2 presents the proposed evaluation method, explaining its importance and the methodological framework. Section 3 delivers the analysis and outcomes, while Section 4 summarizes the main conclusions and implications of the research.

2. Methodology

Figure 1 illustrates a structured flowchart that outlines the key research activities conducted in this study. The process begins with an extensive review of existing PV enhancer evaluation methods to identify their limitations and areas for improvement. Based on these insights, a new method is developed, incorporating the power performance factor.

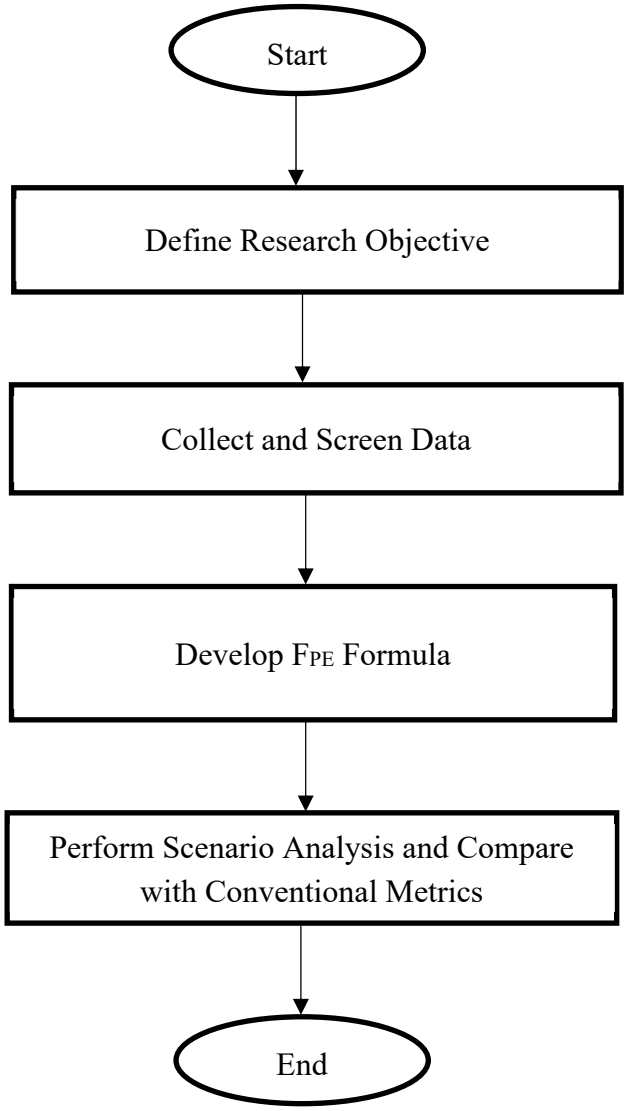

Figure 1. A flowchart illustrating the research methodology.

Next, the work examines the impact of key parameters on the proposed method to assess their influence on evaluation outcomes. Finally, the applicability of the approach is tested across various PV enhancers to validate its effectiveness, ensuring its robustness and reliability. The flowchart visually represents the logical progression of the study, from theoretical analysis to practical implementation, providing a clear overview of the research framework. In the previous work, the electrical outputs of the PV modules—both the enhanced (P_{PVE}) and reference (P_{PV}) systems—were measured using the NI-T UT33D+ Palm Size Digital Multimeter (UNI-TREND, China), capable of measuring DC voltage (0–600 V) with an accuracy of ± (0.5% + 2 digits) and a current up to 10 A with ± (1.5% + 3 digits) accuracy. Voltage and current readings were recorded manually at fixed time intervals under stable irradiance conditions. Identical resistive loads were applied across both systems to ensure consistent and fair performance comparison.

Solar irradiance was measured using the RS PRO 1065313 Solar Meter (IM750) (RS Pro, Taiwan, China), a handheld device with a 3-digit LCD and a measurement range of 0–1999 W/m^2. Its accuracy is specified as ±10 W/m^2 or ±5% (whichever is greater). The device was positioned in the same plane and tilt as the PV modules, and readings were taken during peak daylight periods under clear-sky conditions. The instrument was

verified against a known reference device under natural sunlight prior to the experimental campaign.

Ambient temperature was recorded using a Testo 174T temperature data logger (Testo SE & Co. KGaA, Titisee-Neustadt, Germany), accurate to ±0.5 °C. The sensor was installed in a shaded, ventilated enclosure adjacent to the test modules to minimize radiant heat interference. All instruments were calibrated or verified for accuracy according to manufacturer specifications before data collection commenced.

2.1. The Novel Power Effectiveness Factor, F_{PE}

The power effectiveness factor for a PV enhancer, F_{PE}, is calculated by summing the net power gain obtained from integrating the enhancer with the PV module (P_{PVE}) and the output power of the PV module without an enhancer (P_{PV}). This sum is then divided by the PV module's maximum power ($P_{PV,max}$) under standard test conditions (STCs). This metric offers a normalized evaluation of the total practical power performance of both enhanced and reference PV modules relative to the rated power under Standard Test Conditions (STCs). It enables the benchmarking of the effectiveness of enhancements under real-world conditions and helps identify whether the actual combined output approaches or surpasses idealized expectations. It is acknowledged that the use of the PV module's rated STC power ($P_{PV,max}$) as a benchmark in the F_{PE} metric may introduce a theoretical ceiling that does not always reflect real-world operating limits. However, this ceiling is retained to provide a standardized and technology-neutral reference, allowing for consistent comparison across modules and systems. While an F_{PE} value of 1 implies that the system reaches its STC-rated performance, it does not suggest that this is always practically attainable. Rather, it offers a normalized framework to gauge enhancement effectiveness relative to the module's full rated capacity, helping identify whether the system remains significantly underutilized or is nearing its theoretical maximum. The F_{PE} is formulated as follows:

$$F_{PE} = \frac{P_{PVE} + P_{PV}}{P_{PV,max}}, \tag{1}$$

The improvement in net power output as a result of adding the enhancer to the PV system is denoted as P_{PVE} and is calculated as the difference between the power output of the PV module with the enhancer ($P_{PVE,total}$) and the output power of the PV module without the enhancement method (P_{PV}). This relationship is expressed as follows:

$$P_{PVE} = P_{PVE,total} - P_{PV,} \tag{2}$$

where

$$P_{PVE,total} = I_{PVE,total}\, V_{PVE}, \tag{3}$$

and

$$P_{PV} = I_{PV}\, V_{PV}, \tag{4}$$

I_{PV} and $I_{PVE,total}$ represent the electrical current produced from the PV without and with the enhancer, respectively. On the other hand, V_{PV} and V_{PVE} are the voltages generated from the PV without and with the enhancer, respectively.

To express F_{PE} as a percentage, the following formulation can be used:

$$F_{PE}(\%) = \frac{P_{PVE} + P_{PV}}{P_{PV,max}} \times 100. \tag{5}$$

To assess the measurement reliability of P_{PV} and P_{PVE}, uncertainty analysis was performed using standard error propagation methods. Power was computed as $P = V \times I$. The combined uncertainty in power was calculated as follows:

$$\Delta P = P \times \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (6)$$

where ΔV and ΔI represent absolute voltage and current uncertainties, respectively. Repeated measurements under stable irradiance should be averaged, and standard deviation should be included where applicable. All power values in the F_{PE} analysis should be presented with their corresponding $\pm$ uncertainty margins. This allows the differences in F_{PE} between enhancement designs to be interpreted within a statistically valid confidence range.

The F_{PE} metric is designed to be universally applicable to a wide range of photovoltaic (PV) technologies, including but not limited to monocrystalline silicon, polycrystalline silicon, and thin-film PV modules such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). The formulation relies solely on fundamental, system-level parameters—namely the output power from the PV system with and without enhancement—rather than material-specific electrical or optical properties.

Although the experimental validation in this study utilized crystalline silicon PV modules, the proposed F_{PE} framework can be readily adopted for other PV technologies, provided that the necessary input parameters are available. This makes F_{PE} a technology-independent and practical tool for evaluating the power-effectiveness of PV performance enhancement techniques across diverse applications.

It is important to note that inaccurate or incomplete performance metrics can lead to the suboptimal selection of PV enhancers, potentially limiting energy yield improvements or increasing system costs without proportionate benefit.

While the use of $P_{PV,max}$ (STC) as a benchmark in the F_{PE} metric may appear to disadvantage high-performance modules—since they operate close to their theoretical limit—it serves a distinct purpose. Rather than highlighting absolute gains, F_{PE} emphasizes how effectively a PV enhancer helps a system approach its maximum rated output. This normalization is particularly useful for identifying systems with greater latent potential and avoids overvaluing minor gains in already optimized modules. Although this may result in lower F_{PE} scores for high-performing systems, it ensures a more objective and capacity-aware comparison across different module designs and operational conditions.

2.2. Significance of the Value of F_{PE}

According to Equation (1), the values of F_{PE} can be categorized as follows:

1. If $F_{PE} = 1$, this signifies that the PV enhancer has achieved its optimum performance, maximizing the enhancement of the PV system.
2. If $F_{PE} = \frac{P_{PV}}{P_{PV,max}}$, this suggests that its contribution to system performance is at its lowest level.
3. The PV enhancer power factor should be in the range of $\frac{P_{PV}}{P_{PV,max}}$ and 1, as the indicated below.

$$\frac{P_{PV}}{P_{PV,max}} \leq F_{PE} \leq 1. \quad (7)$$

To ensure accurate and consistent comparisons when using the power effectiveness factor, several essential conditions must be satisfied. First, all performance assessments should be conducted under identical environmental conditions—such as solar irradiance, air speed, ambient temperature, and panel tilt angle—to provide a standardized baseline for evaluating PV performance across different studies. Second, the same model of PV module must be employed in both the baseline (without cooling) and enhanced (with cooling) configurations to eliminate variations stemming from differing module characteristics.

Third, the surface area of the PV coolers should remain consistent, as differences in size can affect heat dissipation and power generation, potentially compromising the integrity of the performance evaluation.

To ensure accurate and consistent comparisons when using the power effectiveness factor, the following conditions must be met:

1. Uniform environmental conditions:

Performance assessments must be conducted under identical conditions such as the following:

- Solar irradiance;
- Air speed;
- Ambient temperature;
- Panel tilt angle.

This establishes a standardized baseline for evaluating PV performance across different studies.

2. Same PV module model:

Both the baseline (without cooling) and enhanced (with cooling) configurations should use the same PV module model.

This avoids discrepancies caused by differences in module specifications.

3. Consistent surface area of PV coolers:

The surface area of the PV coolers must be uniform.

Variations in size can influence the following factors:

- Heat dissipation;
- Power output.

Inconsistent areas can compromise the reliability of the performance evaluation.

Although the current study uses steady-state input conditions, the F_{PE} metric remains applicable even when PV enhancers exhibit nonlinear trade-offs, such as temperature-dependent or irradiance-dependent behaviors. This is because F_{PE} does not rely on a linear assumption; it simply normalizes the observed combined power output against the rated capacity. For nonlinear systems, F_{PE} can be extended or tracked across varying inputs (e.g., time, temperature, or irradiance) to characterize the enhancer's dynamic performance range.

3. Results and Discussion

This section establishes the practical relevance of the new approach by providing validation of its effectiveness through real-world data. Furthermore, an in-depth evaluation is performed to examine how critical parameters influence the effectiveness factor F_{PE}, specifically focusing on P_{PVE}, P_{PV}, and $P_{PV,max}$. The results show that both P_{PVE} and P_{PV} exhibit a direct correlation with F_{PE}; as these power outputs increase, the value of the effectiveness factor also rises. On the other hand, an inverse correlation is identified between $P_{PV,max}$ and F_{PE}, indicating that a higher maximum power rating under STCs tends to lower the effectiveness factor.

3.1. The Application of the Proposed Method on a Real-World Scenario

Table 2 presents the F_{PE} analysis for the evaluated PV system with and without a reflector (Figure 2). The values for P_{PV} and $P_{PV,max}$ are sourced from Ref. [22]. Given that the maximum power under STCs ($P_{PV,max}$) is 525 W, the power output of the PV module without a reflector (P_{PV}) is 110.80 W, and the enhanced power from the enhancer (P_{PVE}) is 16.16 W, the effectiveness factor (F_{PE}) is 0.24, calculated using Equation (1). The results

confirm that the proposed method is applicable for real-world scenarios. This finding serves as evidence supporting the practical utility of the F_{PE} approach, suggesting its potential adoption by PV enhancer designers, researchers, and manufacturers for performance evaluation and optimization.

Table 2. The F_{PE} analysis for the examined PV with a reflector.

Method	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
F_{PE} (current study)	16.16	110.86	525	0.24

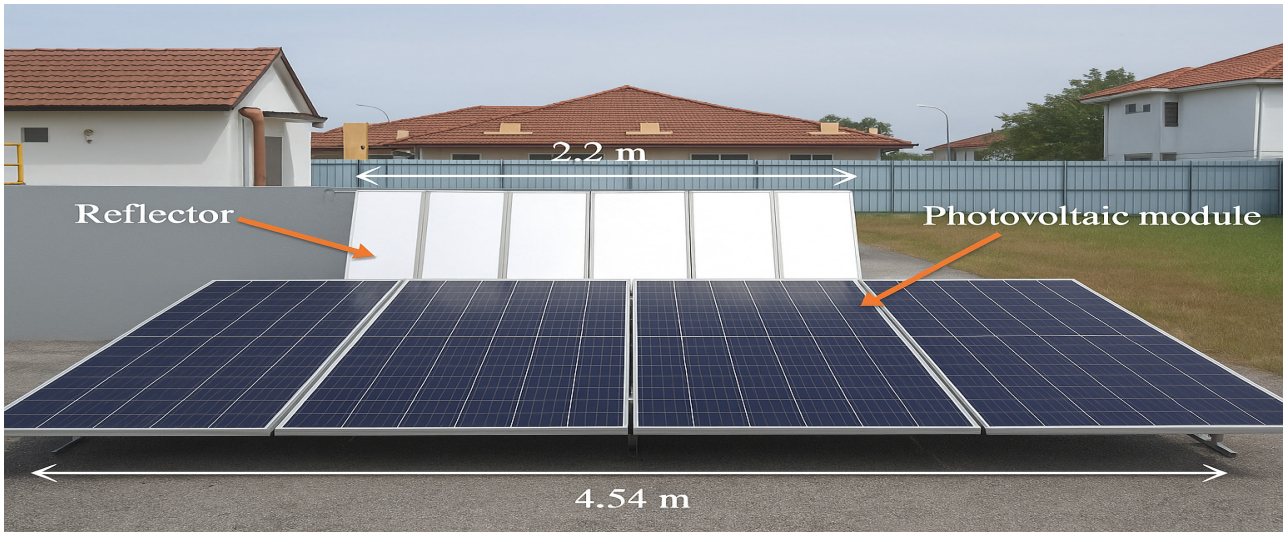

Figure 2. The experimental setup for a PV with a reflector, modified from Ref. [22].

An additional experimental evaluation of the F_{PE} was performed, as shown in Table 3, utilizing data from Ref. [23]. This analysis aimed to assess and compare the performance of photovoltaic modules equipped with either single or double reflectors. Based on the findings in Ref. [23], the power output from the PV module without any reflector was 0.374 W, while the net power gains with a single and double reflector were 0.205 W and 0.218 W, respectively. The maximum rated power of the PV module ($P_{PV,max}$) was 1.25 W.

Table 3. The F_{PE} analysis for a photovoltaic module equipped with single and double reflectors.

Enhancer Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
Single	0.205	0.374	1.25	0.46
Double	0.218	0.374	1.25	0.47

Applying Equation (1), the F_{PE} values were determined to be 0.46 for the single-reflector setup and 0.47 for the double-reflector configuration. These results demonstrate that the double reflector offers a slight performance improvement over the single reflector. Overall, the analysis confirms that F_{PE} is an effective and dependable metric for comparing different PV enhancement methods.

3.2. Further Analysis of F_{PE}

3.2.1. The Impact of the F_{PE} on Different PV Enhancers

To support the analysis of F_{PE}, Table 4 presents data derived from the illustrative example introduced earlier. The table evaluates three designs of PV coolers—Design A, Design B, and Design C—each contributing additional power enhancements of 2 W, 3 W,

and 4 W, respectively. The baseline PV module, operating without any cooling enhancement, produces 10 W, while its rated maximum power output under standard test conditions (STCs) is 15 W. It should be stressed that the PV coolers labeled as Design A, Design B, and Design C in this study were arbitrarily selected to illustrate the flexibility and applicability of the proposed F_{PE} metric. These designs do not represent specific physical designs or technologies, and the input values used (e.g., power outputs) are assumed for the sake of comparative analysis. As such, there is no need to justify the rationale of the selected values, since they do not influence the mathematical validity or interpretability of the F_{PE} method. This approach allows for generalizable insights into how different levels of enhancement performance affect the F_{PE} outcome, independent of specific material or design choices.

Table 4. Comparative evaluation of various PV cooler designs based on F_{PE} metric.

PV Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	2	10	15	0.80
B	3	10	15	0.87
C	4	10	15	0.93

Using Equation (1), the calculated F_{PE} values are 0.8 for Design A, 0.87 for Design B, and 0.93 for Design C. The highest F_{PE} value of 0.93 corresponds to Design C, indicating its superior performance compared to Design A and Design B. However, the optimal PV cooler would achieve an F_{PE} value of unity, which corresponds to an additional power output of 5 W. It is important to note that the F_{PE} value of 0.93 for Design C in this study does not indicate a physical performance limit of a real system, but rather reflects an assumed near-optimal scenario chosen to demonstrate the behavior of the F_{PE} metric when enhancement gains approach saturation. In practical systems, such plateaus may result from thermal saturation, environmental constraints, or system-level losses that limit further performance improvement, even with advanced cooling. However, in this case, the value is part of an illustrative dataset and should not be interpreted as a material or design limitation.

These results demonstrate that F_{PE} effectively distinguishes the performance of PV enhancers by incorporating power into the assessment. Additionally, it provides valuable insight into the maximum achievable performance of a PV enhancer, making it a useful tool for researchers and designers.

The results derived from the new evaluation method (Table 4) largely align with those of the existing method (Table 1) in terms of ranking the coolers' performance. However, the key strength of the new method lies in its ability to offer a quantitative assessment of how closely each cooler approaches the theoretical maximum performance, which is defined as one. This crucial detail is absent in the traditional approach.

For example, although both methods identify Design C as the top performer compared to designs A and B, the conventional method does not clarify whether Design C is nearing its peak potential or still has considerable room for enhancement. In contrast, the new method reveals that Design C reaches only 93% of the maximum possible performance, highlighting the opportunity for further improvement. This ability to express performance relative to the ideal benchmark makes the new method significantly more insightful and practical for guiding optimization efforts.

3.2.2. Impact of Varying P_{PVE} on the F_{PE} Factor

Assuming that the net power outputs of the PV coolers in Table 4 are increased to 3 W, 4 W, and 5 W for Design A, Design B, and Design C, respectively—while keeping all other variables constant—the corresponding F_{PE} values, computed using Equation (1), are 0.87 for Design A, 0.93 for Design B, and 1.00 for Design C (see Table 5). Among the

three configurations, Design C achieves maximum theoretical performance, as indicated by its F_{PE} value of unity, meaning that its combined output equals the rated capacity of the PV module under STCs. This indicates that it is operating at full effectiveness in enhancing the PV system, positioning it as the most efficient cooler under the given conditions.

Table 5. Comparison of PV coolers based on F_{PE} as the net output power from the cooler increases.

PV Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	3	10	15	0.87
B	4	10	15	0.93
C	5	10	15	1.00

When the net output power of the PV coolers presented in Table 5 is reduced to 1 W, 2 W, and 3 W for Design A, Design B, and Design C, respectively—while keeping all other parameters constant as shown in Table 6—the updated F_{PE} values are 0.85 for Design A, 0.88 for Design B, and 0.87 for Design C. Despite Design C still demonstrating the highest relative performance, it no longer reaches the theoretical maximum effectiveness indicated by an F_{PE} value of 1. This outcome supports the observed proportional relationship between net power output and the F_{PE} metric, indicating that an increase in output power leads to higher F_{PE} values. Therefore, the net power contributed by the PV cooler is a critical factor that significantly impacts the overall effectiveness of PV enhancement strategies.

Table 6. Comparison of PV coolers based on F_{PE} under a decreasing net power output from the cooler.

PV Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	1	10	15	0.73
B	2	10	15	0.80
C	3	10	15	0.87

3.2.3. Impact of Varying P_{PV} on F_{PE}

If the power output of the PV without a cooler is decreased from 10 W to 7 W—while all other parameters remain constant, as outlined in Table 7—the updated F_{PE} values become 0.60 for Design A, 0.67 for Design B, and 0.73 for Design C. Under these conditions, Design C continues to deliver the highest effectiveness in terms of power performance compared to the other cooler designs. This outcome further emphasizes the utility of F_{PE} as a reliable metric for assessing the efficiency of PV coolers under different operating scenarios.

Table 7. Comparison of PV coolers based on F_{PE} when the baseline PV power output (without a cooler) is reduced.

PV Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	2	7	15	0.60
B	3	7	15	0.67
C	4	7	15	0.73

When P_{PV} is increased from 7 W to 8 W—while keeping all other conditions constant, as detailed in Table 8—the F_{PE} values are 0.67 for Design A, 0.73 for Design B, and 0.80 for Design C. Compared with the values in Table 7, Design C consistently maintains the highest level of power enhancement effectiveness. These findings underscore the effect of the baseline PV module output on the F_{PE} metric and its importance in accurately assessing the performance of PV cooling systems.

Table 8. Comparison of PV enhancers based on F_{PE} when P_{PV} is increased.

Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	2	8	15	0.67
B	3	8	15	0.73
C	4	8	15	0.80

A direct correlation is observed between the power generated by a PV module without a cooler and the value of F_{PE}; as the baseline power output of the module increases, F_{PE} also rises. This highlights the importance of the PV module's original performance as a critical parameter that shapes the evaluation of PV cooler effectiveness and contributes significantly to overall system assessment.

3.2.4. Impact of Varying $P_{PV,max}$ on F_{PE}

When $P_{PV,max}$ is increased from 15 W to 20 W—while all other variables remain unchanged, as shown in Table 9—the recalculated F_{PE} values are 0.60 for Design A, 0.65 for Design B, and 0.70 for Design C. In this case, Design C still achieves the highest effectiveness in enhancing power performance. These results emphasize the impact of the module's STC-rated power on the F_{PE} metric, confirming its significance as a determining factor in the assessment of PV cooler efficiency.

Table 9. Comparison of PV enhancers based on F_{PE} when $P_{PV,max}$ is increased.

Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	2	10	20	0.60
B	3	10	20	0.65
C	4	10	20	0.70

When the $P_{PV,max}$ is decreased from 20 W to 18 W—while keeping all other parameters constant, as presented in Table 10—the updated F_{PE} values become 0.67 for Design A, 0.72 for Design B, and 0.78 for Design C. A comparison with Table 9 confirms that Design C continues to deliver the highest level of power enhancement. This outcome further reinforces the inverse relationship between the PV module's STC-rated power and the F_{PE} value, highlighting its importance as a critical variable in evaluating the performance of PV cooling systems.

Table 10. Comparison of PV coolers based on F_{PE} when $P_{PV,max}$ is increased.

Cooler Design	P_{PVE}, W	P_{PV}, W	$P_{PV,max}$, W	F_{PE}
A	2	10	18	0.67
B	3	10	18	0.72
C	4	10	18	0.78

An inverse correlation exists between the $P_{PV,max}$ and the F_{PE} factor; as the rated maximum power rises, the corresponding F_{PE} value declines. This finding underscores the importance of the STC-rated power as a key determinant in calculating F_{PE}, thereby significantly affecting the evaluation of PV cooler performance.

3.3. A Summary Between the Existing and the New Methods

The results demonstrate that the new method can effectively compare different designs of PV enhancers, similar to the existing method. While conventional evaluation metrics typically focus on absolute power gains, these alone can overlook the remaining performance

potential of a PV system. The proposed F_{PE} uniquely addresses this by benchmarking the combined actual output (enhanced + baseline) against the module's rated maximum power under STCs. This normalization effectively quantifies the unrealized performance potential—i.e., the gap between observed operation and the theoretical maximum. By doing so, it helps identify whether an enhancer is enabling substantial additional output or if the system is approaching its upper performance limit. This facilitates more informed decisions in technology selection and prioritization, especially when comparing enhancers across modules with varying capacities.

On the other hand, Table 11 shows the importance of distinguishing the proposed F_{PE} metric from other widely used performance indicators such as the Energy Payback Time (EPBT) and Performance Ratio (PR). While the EPBT evaluates how quickly a system can offset its embodied energy and the PR accounts for total system losses relative to ideal energy output, both metrics are oriented toward long-term energy sustainability or system-wide efficiency. In contrast, F_{PE} is a short-term, power-based, and enhancement-specific metric that directly compares the combined power output of enhanced and baseline PV systems against the module's rated maximum under standard test conditions. This makes F_{PE} especially suited for assessing the incremental performance benefits of enhancement techniques in experimental, prototype, or modular applications.

Table 11. Comparison between F_{PE}, EPBT, and PR.

Aspect	F_{PE}	EPBT	PR
Full Name	Performance Effectiveness Factor	Energy Payback Time	Performance Ratio
Primary Focus	Power gain relative to rated capacity due to enhancer	Time required to recover embodied energy	Ratio of actual to theoretical energy output
Purpose	Evaluate short-term effectiveness of PV enhancers	Assess life-cycle energy sustainability	Measure overall PV system efficiency under real conditions
Input Requirements	Power output of enhanced and baseline PV systems + PV rated power (STCs)	Total embodied energy + annual energy output	Actual energy yield + theoretical energy yield under STCs
Data Timescale	Instantaneous or short-term power data	Long-term (usually annual or lifetime) energy data	Monthly or annual energy data
Use Case	Lab tests, comparative studies, prototype screening	Life cycle assessment, sustainability studies	Field performance monitoring, benchmarking
Output Format	Dimensionless ratio	Time (years)	Percentage or decimal ratio
Normalization	Normalized to PV rated output ($P_{PV,max}$)	Not normalized to rated power	Normalized to theoretical energy output

4. Conclusions

This research introduces an innovative approach for evaluating the effectiveness of PV enhancers by integrating three key parameters: P_{PVE}, P_{PV}, and $P_{PV,max}$. The method assesses enhancer performance by examining how each of these parameters influences the effectiveness factor F_{PE}. The results indicate that F_{PE} increases proportionally with both the net power gain and the baseline output of the PV module, while it decreases as the STC-rated power increases. Based on this framework, the enhancer reaches peak performance when F_{PE} equals one, and its lowest effectiveness is represented by the ratio between the PV's unenhanced output and its maximum STC power. The practicality of the proposed method was validated using experimental data from previous studies, confirming its real-world applicability. To ensure reliable comparisons when using the PV cooler power and cost effectiveness factor, several conditions must be met. Performance assessments

should be conducted under identical operating conditions—including ambient temperature, solar irradiance, air speed, and PV module tilt angle—to ensure consistency. The same design of PV module should be used for both the reference (uncooled) and cooled setups to avoid specification differences. Additionally, the surface area of the PV coolers should remain consistent, as variations can affect heat dissipation and energy output, potentially distorting results. These findings demonstrate the utility of this approach in categorizing PV enhancers and offer a practical tool for use by engineers, developers, and researchers. Further investigations are recommended to expand on this evaluation framework and support ongoing improvements in PV system performance assessment.

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Nomenclature

F	Factor, dimensionless
I	Electrical current, (Ampere)
P	Power, (W)
PV	Photovoltaic module
PVE	PV with an enhancer
PVT	Photovoltaic thermal collector
V	Voltage, (V)
Subscript	
PE	Power effectiveness
max	Maximum output power
ref	Reference
STC	PV's standard test conditions

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