

Article

Evaluation of Photovoltaic Module Enhancer Performance: Examining a New Factor for Cost and Energy Effectiveness

Sakhr M. Sultan¹ and Tso Chih Ping^{2,*} ¹ Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia; mas2007_eng@yahoo.com² Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Melaka 75450, Malaysia

* Correspondence: cptso@mmu.edu.my (T.C.P.)

Abstract

Photovoltaic (PV) enhancement technologies, including cooling systems, reflectors, and tracking mechanisms, are widely employed to improve the electrical performance of PV systems. However, the effectiveness of these technologies should be evaluated not only in terms of performance improvement but also by considering the associated implementation costs. To address this need, previous studies introduced the Cost Effectiveness Factor (F_{CE}), which integrates power output and manufacturing cost into a single performance indicator. While F_{CE} is useful for short-term and experimental assessments, it is based on instantaneous power output and does not account for the cumulative energy generated over extended operating periods. Furthermore, many experimental and field studies on PV enhancement technologies, particularly PV cooling systems, report their performance in terms of energy generation (kWh) rather than instantaneous power output (W), creating a need for an energy-based assessment methodology. Therefore, this study proposes a new Cost–Energy Effectiveness Factor (F_{CEE}) that extends the concept of F_{CE} by incorporating energy output instead of power output, thereby enabling a more comprehensive evaluation of long-term techno-economic performance. The proposed indicator integrates the output energy of PV systems with and without enhancers, the manufacturing cost of PV enhancers, and the unit cost of PV electricity into a single dimensionless factor. In addition, a theoretical minimum value ($F_{CEE,min}$) is introduced to establish a benchmark for performance evaluation. Comprehensive sensitivity analyses were performed to investigate the influence of key technical and economic parameters, including the output energy of the enhanced and unenhanced PV systems, manufacturing cost, the unit PV electricity cost, and maximum output power under standard test conditions. The results indicate that F_{CEE} decreases with increasing enhanced PV energy output and electricity value; however, it increases with higher manufacturing costs and greater energy production from the reference PV system. In contrast, variations in the maximum output power affect only the benchmark value ($F_{CEE,min}$) without influencing the actual F_{CEE} values. The proposed indicator was further validated using data obtained from real photovoltaic cooling systems, demonstrating its applicability under practical operating conditions and confirming its suitability for real-world PV enhancement scenarios. Compared with F_{CE} , the proposed F_{CEE} provides a more realistic representation of the long-term benefits of PV enhancement technologies because it evaluates accumulated energy generation rather than instantaneous power output. The indicator successfully differentiates between effective, neutral, and ineffective PV enhancers and offers a practical tool for researchers, designers, manufacturers, and investors seeking to compare PV enhancement technologies from both energy and economic perspectives. Consequently, F_{CEE} can serve as an effective



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preliminary screening and comparative assessment tool for PV enhancement technologies, thereby promoting the efficient utilization of sustainable energy resources, while detailed investment decisions should be supported by comprehensive techno-economic analyses that consider lifecycle costs, discount rates, financing conditions, and other project-specific economic factors.

Keywords: solar energy; photovoltaic module; PV enhancer; energy and cost effectiveness; assessment; sustainability

1. Introduction

Energy is widely recognized as a key contributor to human welfare and economic growth [1–3]. Since ancient times, solar energy has been utilized for essential purposes such as heating and food preservation. With continuous technological advancements, solar energy has increasingly been exploited for thermal and electrical power generation [4]. Among the available technologies, photovoltaic (PV) modules have emerged as one of the most effective systems for directly converting solar radiation into electricity [5]. Consequently, the global deployment of PV systems has expanded rapidly over the past decade [6]. Worldwide PV electricity generation increased substantially from 32.2 TWh in 2010 to 1002.9 TWh in 2021, representing an increase of more than thirty times within eleven years. This remarkable growth has motivated extensive research aimed at improving PV performance through various enhancement techniques, including cooling systems and solar reflectors.

The selection of an appropriate enhancement approach largely depends on local climatic conditions. In areas characterized by high solar irradiance and elevated ambient temperatures, PV cooling technologies are generally preferred because they reduce module operating temperature and improve electrical performance. Enhanced heat transfer through fluid motion promotes more effective heat dissipation from the PV surface [7–12], thereby increasing system efficiency [7]. Various cooling strategies have been developed, including passive and active systems, natural and forced convection methods, and cooling media such as air, liquids, and phase-change materials (PCMs). Considerable attention has been devoted to the development of PV cooling devices fabricated from thermally conductive materials, including aluminum, copper, stainless steel, and other metals, to maximize heat removal. Nevertheless, the service life of these cooling devices may be affected by environmental and weather conditions [13].

A study investigated the performance of several low-cost passive cooling techniques for photovoltaic (PV) systems operating under tropical climatic conditions [14]. The cooling configurations included metal pellets/phase-change material (PCM), porous silicon carbide (SiC) ceramic/PCM, aluminum shavings/PCM, porous SiC ceramic/water, and cellulose pads/water. Experimental results showed that the proposed cooling methods reduced PV operating temperature by 3.2–16.3% and improved electrical efficiency by 1.3–10.6%, with the metal pellets/PCM configuration demonstrating the highest performance enhancement. Economic analysis indicated that the levelized cost of energy (LCOE) ranged from 0.134 to 0.166 USD/kWh. The authors concluded that PCM-based cooling systems employing metal pellets or porous SiC ceramics offer superior thermal and electrical performance while maintaining favorable economic viability. Furthermore, the utilization of industrial waste materials was found to improve system affordability and sustainability.

Another study evaluated the effectiveness of passive cooling using soy wax and paraffin-based phase-change materials (PCMs) attached to the rear surface of PV modules in

tropical environments [15]. The PCM layer absorbed excess thermal energy during periods of high solar irradiance, thereby reducing the operating temperature of the PV panel. Experimental findings revealed that the PCM-based cooling system lowered the panel temperature by up to 10 °C and enhanced voltage stability by approximately 8%, resulting in improved power output and potentially extended module lifespan. Economic assessment showed that the cooled PV system achieved a lower LCOE of 0.068 USD/kWh compared with that of 0.076 USD/kWh for the uncooled PV system. The study demonstrated that PCM-based passive cooling is both technically effective and economically feasible for PV applications in tropical regions.

A further study examined the impact of latent heat storage units (LHSUs) enhanced with fins and iron nanoparticles on the performance of photovoltaic systems. Several configurations were assessed, including conventional PV modules, PV systems integrated with paraffin-filled LHSUs, and LHSUs containing different numbers of fins and nanoparticles [16]. The results indicated that the incorporation of fins and nanoparticles significantly improved heat dissipation, reducing PV surface temperature by 7.28–17.93% and increasing module efficiency by up to 15.51% relative to a conventional PV system. Economic analysis reported an LCOE value of 0.69 USD/kWh for the configuration incorporating six fins, while performance ratio values ranged from 0.597 to 0.689. Environmental assessment showed that although aluminum fins improved system performance with a relatively low environmental impact, the addition of nanoparticles considerably increased environmental burden indicators. The authors concluded that fin- and nanoparticle-enhanced LHSUs can effectively improve PV performance; however, further optimization is required to achieve a balance between technical performance, economic viability, and environmental sustainability.

In contrast, solar reflectors are often more suitable for locations experiencing relatively low solar irradiance and moderate ambient temperatures. The concept of using reflectors to increase the effective solar collection area and enhance PV performance dates back to 1958 [17–21]. Numerous numerical and experimental studies have demonstrated the effectiveness of reflector-based systems. For example, outdoor investigations of PV modules integrated with V-trough concentrators reported maximum power improvements of up to 31.2% [22]. Similarly, reflector optimization studies showed output power enhancements reaching 60% [18], while aluminum sheet reflectors increased power generation by approximately 15% [19]. Another outdoor experiment involving a PV-V-trough configuration achieved a 48% increase in energy production [23]. Furthermore, a combined cooling and reflector system improved PV efficiency to 10.68% while maintaining a payback period of 4.2 years [24]. Computational investigations of aluminum sheet reflector systems revealed that larger reflector tilt angles could further improve PV performance [25]. Additional innovations include curved reflector designs that increased incident solar power by 61% [26], flat-plate reflector and cooling combinations that enhanced PV efficiency by 36% [27], and three-dimensional stainless steel reflector structures capable of achieving PV efficiencies as high as 34.16% [28].

Motivation of the Present Study

Although Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and Lifecycle Cost Analysis (LCCA) are well-established methods for evaluating the economic feasibility of photovoltaic (PV) systems, their application typically requires detailed financial, operational, and lifecycle information that may not be readily available during the development and experimental evaluation stages of PV enhancement technologies. Furthermore, many studies on PV cooling systems, reflectors, and other enhancement approaches primarily report performance improvements in terms of power

output, energy generation, and manufacturing cost, while comprehensive economic data are often unavailable. Consequently, there is a need for simplified assessment methods that can utilize commonly reported experimental parameters while still incorporating economic considerations.

To address this need, a previous study [5] introduced the Cost Effectiveness Factor (F_{CE}) to evaluate PV enhancement technologies using power output and manufacturing cost. The proposed indicator serves as a laboratory-scale performance metric that facilitates the comparison of different PV enhancement technologies under controlled operating conditions. F_{CE} is expressed as

$$F_{CE} = \frac{P_{PV,out} + \frac{Z}{Y}}{P_{PVE,out}}, \quad (1)$$

where $P_{PV,out}$ and $P_{PVE,out}$ are the output power values of the PV system without and with an enhancer, respectively. Y is the cost of one watt of PV power, and Z is the manufacturing cost of the enhancement technology.

Although F_{CE} provides a useful means of evaluating PV enhancement technologies based on power output and cost, it does not account for the cumulative energy generated over extended operating periods. Moreover, many experimental and field studies on photovoltaic cooling technologies report their performance in terms of daily, monthly, or annual energy generation (kWh) rather than instantaneous power output (W). Consequently, the direct application of power-based indicators such as F_{CE} may not fully capture the long-term energy benefits achieved by PV enhancement technologies under real operating conditions. Since energy generation is a key factor influencing the economic viability of PV enhancement technologies, an energy-based assessment method is required.

Therefore, this study introduces a new Cost Effectiveness Factor (F_{CEE}) that extends the concept of F_{CE} by integrating the output energy of PV systems with and without enhancers, the manufacturing cost of the enhancer, and the unit cost of PV electricity into a single performance indicator. In addition, the proposed factor is validated using data obtained from real photovoltaic cooling systems to examine its applicability under practical operating conditions. Compared with F_{CE} , the proposed F_{CEE} provides a more realistic representation of the long-term benefits of PV enhancement technologies because it evaluates accumulated energy generation rather than instantaneous power output. F_{CEE} promotes more efficient utilization of sustainable energy resources.

Accordingly, the objectives of this study are to (i) introduce the F_{CEE} as a new assessment method for photovoltaic enhancement technologies; (ii) investigate the influence of key technical and economic parameters through sensitivity analyses; (iii) compare the characteristics of F_{CEE} with the previously developed F_{CE} ; and (iv) demonstrate the applicability of the proposed factor using real-world photovoltaic cooling systems.

2. Research Methodology

The first stage involves a comprehensive review of existing PV cooling techniques and the associated methods used to evaluate the performance of these techniques. This review facilitates the identification of current research gaps and provides a deeper understanding of the limitations of existing approaches, leading to the development of a new evaluation method, namely the Cost–Energy Effectiveness Factor (F_{CEE}). The proposed indicator is based on the relationship between the energy performance of PV enhancers and their associated manufacturing costs. In addition, the applicability conditions and limitations of the proposed method are clearly defined. In the second stage, the minimum value of the Cost–Energy Effectiveness Factor ($F_{CEE,min}$) is derived and introduced as a benchmark for assessing the minimum acceptable performance of PV enhancers. The significance and

interpretation of F_{CEE} are also discussed in this stage. The third stage focuses on validating the applicability of the proposed method using several hypothetical PV enhancer models with varying performance characteristics. Finally, a parametric analysis is conducted to investigate the influence of key variables on the proposed indicator. These variables include the manufacturing cost of the PV enhancer, the energy output of the PV system with an enhancer, the energy output of the conventional PV system without an enhancer, and the unit cost of PV electricity generated by the PV system.

2.1. The New Cost–Energy Effectiveness Factor (F_{CEE})

The Cost–Energy Effectiveness Factor (F_{CEE}) is defined as the ratio of the combined contribution of the output energy from a PV system without an enhancer and the energy-equivalent manufacturing cost of the enhancer to the output energy of a PV system with an enhancer. The factor is expressed as

$$F_{CEE} = \left(\frac{E_{PV,out} + \frac{Z}{U}}{E_{PVE,out}} \right), \quad (2)$$

It is important to note that F_{CEE} relies on four parameters: the manufacturing cost of the PV enhancer (Z), the one-unit cost of PV electricity without an enhancer (U), the output energy from a PV system without an enhancer ($E_{PV,out}$), and the output energy from a PV system with an enhancer ($E_{PVE,out}$).

The primary objective of F_{CEE} is to evaluate the cost–energy effectiveness of photovoltaic enhancement technology by simultaneously considering two fundamental aspects: (i) the total electrical energy generated by the enhanced PV system and (ii) the economic investment associated with implementing the enhancement technology. The formulation was intentionally designed to remain simple and practical while preserving a clear physical interpretation and facilitating straightforward application by researchers, engineers, and industry practitioners.

From a physical perspective, the denominator, $E_{PVE,out}$, represents the total energy generated by the enhanced PV system, which is the principal benefit obtained from implementing the enhancement technology. The numerator, $E_{PV,out} + \frac{Z}{U}$, consists of two components. The first component, $E_{PV,out}$, represents the energy that would have been generated by the reference PV system without enhancement. The second component, $\frac{Z}{U}$, converts the manufacturing cost of the enhancement technology into an equivalent energy value using the unit electricity cost. This conversion establishes a common basis between economic cost and energy production, thereby enabling a unified cost–energy assessment framework.

Consequently, F_{CEE} may be interpreted as the ratio between the total equivalent energy investment and the total energy delivered by the enhanced PV system. Lower F_{CEE} values indicate that a greater amount of useful energy is obtained for a given economic investment, while higher values indicate reduced economic effectiveness. Therefore, the proposed indicator provides a direct measure of the energy return achieved relative to the combined energy-equivalent investment associated with the PV enhancement technology.

It should be emphasized that the proposed F_{CEE} is not intended to replace comprehensive economic assessment methods such as the Levelized Cost of Electricity (LCOE) or Net Present Value (NPV). While LCOE and NPV provide detailed economic evaluations by considering lifecycle costs, discount rates, financing conditions, and long-term financial performance, they require extensive economic data that are often unavailable during the early stages of PV enhancement technology development. In contrast, F_{CEE} is designed as a simple preliminary screening and comparative assessment tool that utilizes a limited number of parameters commonly reported in experimental studies. Therefore, F_{CEE} should

be regarded as a complementary indicator that can support the initial evaluation and comparison of PV enhancement technologies before more detailed techno-economic analyses are performed.

2.2. The Minimum Value of Energy and Cost Effectiveness Factor, $F_{CEE,min}$

The minimum Cost–Energy Effectiveness Factor ($F_{CEE,min}$) is defined as the theoretical lower bound of the proposed F_{CEE} indicator. It represents the most favorable cost–energy performance that can be achieved by photovoltaic enhancement technology under a given set of operating conditions. The factor is determined by comparing the output energy of the reference PV system without an enhancer to the maximum achievable energy output of the enhanced PV system operating under standard test conditions. Consequently, $F_{CEE,min}$ serves as a benchmark against which the effectiveness of PV enhancement technologies can be evaluated. Values of F_{CEE} that are closer to $F_{CEE,min}$ indicate superior cost–energy effectiveness and a more favorable balance between energy generation and economic investment. $F_{CEE,min}$ can be represented as follows:

$$F_{CEE,min} = \frac{E_{PV,out}}{t \times P_{PVE,outmax}}. \quad (3)$$

where t is the operating duration in hours, and $P_{PVE,outmax}$ is the maximum output power of the PV system with an enhancer under standard test conditions.

2.3. Significance of F_{CEE} Value

According to Equation (2), F_{CEE} can manifest in three potential scenarios:

1. If $F_{CEE} > 1$, it signifies that the PV enhancer is not cost-effective.
2. If $F_{CEE} = 1$, it indicates that the PV enhancer is neutral and meets a certain threshold value.
3. If $F_{CEE,min} \leq F_{CEE} < 1$, it suggests that the PV enhancer is cost-effective.

3. Analysis and Discussion of Results

In this section, the presentation of the results and discussion regarding the utilization of the novel method will be carried out. Examples are provided to examine how the application of F_{CEE} and $F_{CEE,min}$ influences performance evaluation. Additionally, this section elaborates in detail on the influential parameters affecting F_{CEE} . It will become evident that the new method enables the assessment of performance and facilitates comparisons between various types of PV enhancers, especially when considering the energy of both the PV systems with and without an enhancer in the analysis. Although a comprehensive uncertainty analysis is beyond the scope of the present study, the robustness of the proposed F_{CEE} metric can be qualitatively assessed based on the sensitivity analysis results. Uncertainties in the enhancement cost (Z), PV electricity value (U), baseline energy output ($E_{PV,out}$), and enhanced energy output ($E_{PVE,out}$) may affect the calculated F_{CEE} value. Systems with F_{CEE} values close to the classification threshold of 1 may be more sensitive to such uncertainties, potentially leading to changes in classification. However, systems exhibiting F_{CEE} values significantly below or above the threshold are expected to retain their classification under reasonable parameter variations. Future studies should incorporate formal uncertainty quantification techniques to evaluate the statistical confidence of F_{CEE} -based assessments.

From a sustainability perspective, the proposed F_{CEE} indicator provides a practical framework for balancing energy performance improvements against the resources required to achieve them. By identifying enhancement technologies that deliver higher energy output relative to their manufacturing cost, the proposed method can support the development and deployment of more resource-efficient photovoltaic systems. Consequently, F_{CEE} may

assist researchers, designers, and decision-makers in selecting technologies that contribute to both economic and energy sustainability.

3.1. Experimental Validation for the New Method and Comparison with the Existing Method

The experimental validation is conducted to support the applicability of the proposed method in a real case study. A previous experimental study was carried out for a PV system with different cooling configurations, as shown in Figure 1 (Harby et al. [29]). The total cost values, including the investment, maintenance and replacement costs, for the three PV cooling configurations were \$171.94, \$168.34 and \$179.04 for PVT steel, PVT aluminum and PVT copper. The total cost value for the PV reference without cooling was \$91.56. The total produced energy values were 428.56, 446.45, 487.17 and 163.41 kWh for PVT steel, PVT aluminum, PVT copper and the PV reference, respectively (shown in Table 1). The one-unit electricity cost for the PV reference is 0.56 \$/kWh. Now, using Equation (2), the F_{CEE} values are 1.1, 1.04 and 0.99 for PVT steel, PVT aluminum and PVT copper, respectively. It can be seen that PVT copper is cost-effective, whereas PVT steel and PVT aluminum are not. Using the existing assessment method, it is shown that PVT copper is better than PVT steel and PVT aluminum. However, it does not directly indicate the cost–energy effectiveness of these cooling configurations.

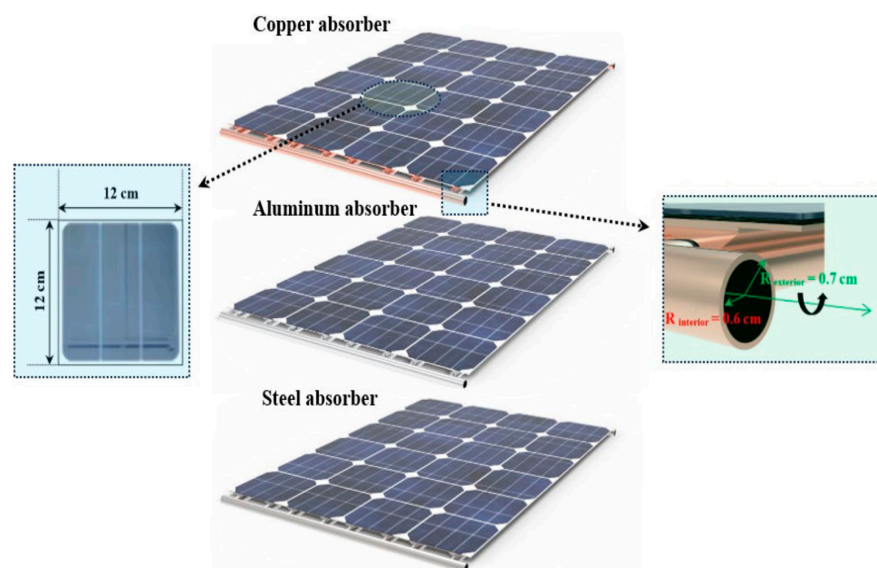


Figure 1. PV systems with different cooling configurations. Adapted from Ref. [26].

Table 1. The energy and cost-effectiveness analysis for a PV system with different cooling configurations using F_{CEE} . Modified from ref. [29].

Type	$E_{PV,out}$, kWh	$E_{PVE,out}$, kWh	U, (\$/kWh)	Z, \$	F_{CEE}	Remark
PV standard	163.41	-	0.56	-	-	-
PVT steel	163.41	428.94	0.56	171.94	1.10	Not cost-effective
PVT Al	163.41	446.45	0.56	168.34	1.04	Not cost-effective
PVT Cu	163.41	487.17	0.56	179.04	0.99	Cost-effective

To further evaluate the applicability of the proposed Cost–Energy Effectiveness Factor (F_{CEE}), experimental data from a previously published outdoor photovoltaic study conducted under Malaysian climatic conditions [30] were utilized. Figure 2 and Table 2 show the experimental setup and PV specifications, respectively. The PV system was operated in its conventional configuration without a reflector during February, while a reflector was incorporated in April. Key meteorological parameters, including daily solar radiation,

ambient temperature, and wind speed, were sourced from the Malaysian Meteorological Department (MMD). These data served as the basis for assessing the energy production, efficiency performance, and economic feasibility of the PV reflector system. In this study, the monthly energy outputs of the PV system without and with a reflector were reported as 106.43 kWh and 121.94 kWh, respectively (see Table 3). The unit electricity cost was assumed to be 1 RM/kWh, while the manufacturing cost of the reflector was RM 250.

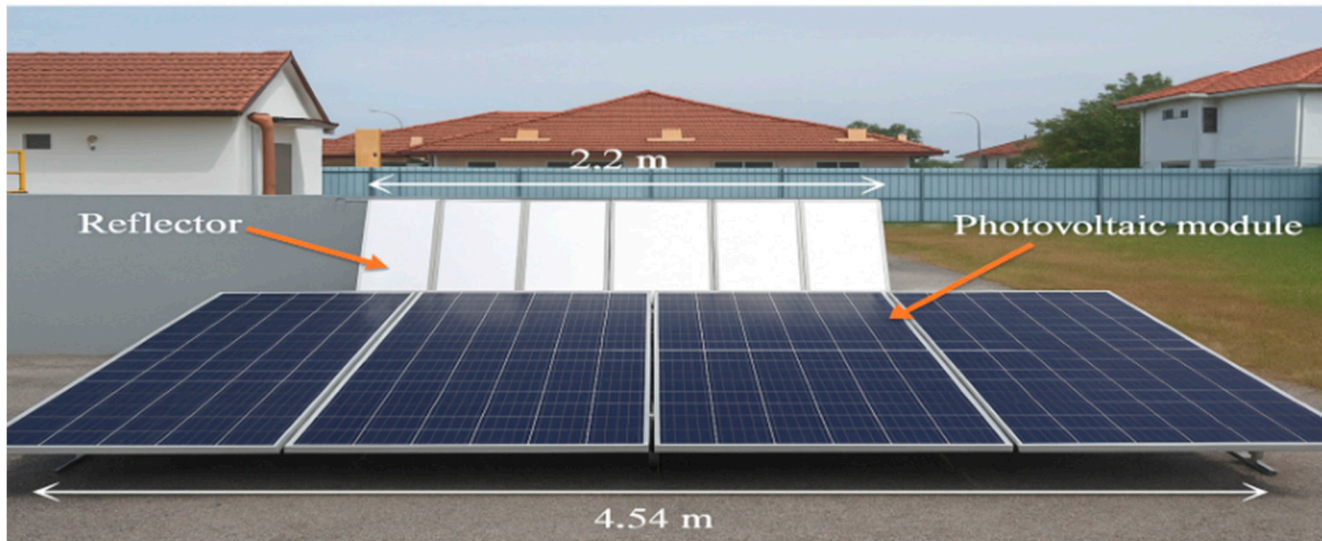


Figure 2. A PV system with a reflector. Adapted from Ref. [30].

Table 2. PV specifications used in the experiment [30].

Parameter	Value
Maximum power (P_{max})	525 Wp
Voltage at maximum power (V_{mpp})	41.15 V
Current at maximum power (I_{mpp})	12.76 A
Open circuit voltage (V_{oc})	49.15 V
Short circuit current (I_{sc})	13.65 A
Panel efficiency	20.3%
Temperature coefficient of P_{max}	$-0.35\%/^{\circ}\text{C}$
Operating temperature range	-40 to $85\text{ }^{\circ}\text{C}$
Panel dimensions (length $\times$ width $\times$ thickness)	2279 mm $\times$ 1134 mm $\times$ 3.5 mm

Table 3. The energy and cost-effectiveness analysis for a PV system with a reflector using F_{CEE} . Modified from Ref. [30].

Type	$E_{PV,out}$, kWh	$E_{PVE,out}$, kWh	U, (RM/kWh)	Z, \$	F_{CEE}	Remark
PV with a reflector	106.43	121.94	1.00	250	0.98	Cost effective

By applying Equation (2), the calculated F_{CEE} value was 0.98. Since this value is less than 1, the reflector-enhanced PV system can be classified as cost-effective according to the proposed assessment framework. The result indicates that the additional energy generated by the reflector is sufficient to justify its associated manufacturing cost under the considered operating conditions.

The successful application of F_{CEE} to experimentally measured outdoor data demonstrates the practical applicability of the proposed methodology for real photovoltaic en-

hancement systems. Furthermore, the analysis confirms that F_{CEE} can be used to quantitatively assess the balance between energy gain and economic investment, thereby providing a straightforward classification of the cost–energy effectiveness of PV enhancement technologies. Unlike conventional power-based effectiveness indicators, the proposed F_{CEE} incorporates cumulative energy generation and is therefore more suitable for evaluating the long-term economic performance of photovoltaic enhancement technologies under actual operating conditions.

3.1.1. The Effects of F_{CEE} and $F_{CEE,min}$ on Different PV Enhancers

To demonstrate the application of F_{CEE} and $F_{CEE,min}$, the data presented in Table 4 were developed based on four hypothetical PV enhancer models. It was assumed that the PV enhancers increased the annual energy output of the PV system to 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The corresponding manufacturing costs of the enhancers were assumed to be \$30, \$32, \$35, and \$40, respectively. For comparison purposes, the annual energy output of the reference PV system without an enhancer was fixed at 110 kWh. In addition, the maximum PV output power under standard test conditions was assumed to be 120 W. The unit PV electricity cost was taken as 0.75 \$/kWh, while the operating period was assumed to be 8000 h.

Table 4. Comparison between different models of PV enhancers using F_{CEE} and $F_{CEE,min}$.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	F_{CEE}	Remark
A	110.00	125.00	30	0.75	0.115	1.200	Not Effective
B	110.00	152.66	32	0.75	0.115	1.000	Neutral
C	110.00	195.83	35	0.75	0.115	0.801	Effective
D	110.00	204.16	40	0.75	0.115	0.800	Effective

Using Equation (2), the calculated F_{CEE} values for Models A, B, C, and D were found to be 1.25, 1.00, 0.80, and 0.80, respectively. The minimum Cost–Energy Effectiveness Factor, $F_{CEE,min}$, was calculated as 0.11. Based on the proposed classification criteria, Model A is considered not cost-effective because its F_{CEE} value exceeds unity. Model B represents a neutral case, with an F_{CEE} value equal to 1.00. In contrast, Models C and D are classified as cost-effective since their F_{CEE} values are below unity. Furthermore, these two models exhibit the most favorable cost–energy performance among the evaluated options because their F_{CEE} values are the closest to the minimum benchmark value, $F_{CEE,min} = 0.11$, indicating superior effectiveness relative to the other models.

3.1.2. The Effect of Changing the Output Energy from a PV System with an Enhancer on F_{CEE}

Table 5 summarizes the calculated values of the proposed F_{CEE} for four hypothetical PV enhancer models characterized by different energy outputs and manufacturing costs. The evaluation was conducted based on a PV system energy output of 110 kWh without enhancement, a PV one-unit cost of electricity of 0.75 \$/kWh, and a PV module with a maximum power output of 120 W operating for 8000 h. Under these conditions, the minimum effectiveness factor, $F_{CEE,min}$, was determined to be 0.115 and subsequently adopted as the reference criterion for assessing performance.

Table 5. Comparison of PV coolers using F_{CEE} when the energy produced from a PV system with an enhancer is increased.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	F_{CEE}	Remark
A	110.00	140.00	30	0.75	0.115	1.071	Not Effective
B	110.00	170.00	32	0.75	0.115	0.898	Effective
C	110.00	219.00	35	0.75	0.115	0.715	Effective
D	110.00	220.00	40	0.75	0.115	0.742	Effective

The results indicate that Models B, C, and D can be considered effective, as their F_{CEE} values fall within the acceptable range, being greater than $F_{CEE,min}$ but less than 1. Conversely, Model A is classified as ineffective because its F_{CEE} value exceeds the threshold value of 1. Among the evaluated models, Model C exhibited the lowest F_{CEE} value of 0.715, signifying the most favorable trade-off between additional energy generation and manufacturing cost. This was followed by Model D and Model B, with F_{CEE} values of 0.742 and 0.898, respectively. These results suggest that improvements in energy production can substantially enhance the cost–energy effectiveness of PV enhancers, even when such improvements are associated with increased manufacturing costs.

Now, the computed values of the newly proposed F_{CEE} were evaluated for four hypothetical PV enhancer configurations operating under low energy yield improvement scenarios. The assessment was conducted using a reference PV system generating 110 kWh of energy without enhancement, a unit PV electricity value of 0.75 \$/kWh, a maximum PV power rating of 120 W, and a cumulative operating time of 8000 h. Based on these assumptions, the minimum acceptable effectiveness factor, $F_{CEE,min}$, was determined to be 0.115 and subsequently used as the benchmark for evaluating the proposed PV enhancers.

The results indicate that all investigated configurations produced F_{CEE} values greater than 1, ranging from 1.256 to 1.339. According to the proposed classification criteria, these values indicate that none of the evaluated PV enhancers can be considered economically effective from a cost–energy perspective. Among the investigated configurations, Model D achieved the lowest F_{CEE} value of 1.256 due to its comparatively higher energy generation of 130 kWh. Nevertheless, its value remained above the effectiveness threshold and therefore could not be classified as a cost-effective design. Similarly, Models A, B, and C produced F_{CEE} values of 1.339, 1.328, and 1.306, respectively, all exceeding the acceptable limit.

These findings demonstrate that modest improvements in energy yield are insufficient to offset the additional manufacturing costs associated with enhancement technologies. As a result, the economic benefits obtained from the increased energy production do not justify the required investment. More generally, the sensitivity analysis reveals that F_{CEE} is highly dependent on the magnitude of the additional energy generated. When the energy gain remains limited, even relatively small enhancement costs may lead to F_{CEE} values above the effectiveness threshold. This observation highlights the importance of achieving substantial energy output improvements when designing PV enhancement technologies, as minor performance gains alone are unlikely to provide satisfactory cost–energy effectiveness.

3.1.3. The Effect of Changing the Energy Produced from a PV System Without an Enhancer on F_{CEE} and $F_{CEE,min}$

Table 6 summarizes the calculated F_{CEE} values for four PV enhancer models under a scenario where the energy output of the baseline PV system is increased from 110 kWh to 115 kWh. The assessment was performed using a one-unit PV electricity cost of 0.75 \$/kWh, a maximum PV power rating of 120 W, and a total operating period of 8000 h. Based on these assumptions, the minimum effectiveness threshold, $F_{CEE,min}$, was calculated as 0.120

and subsequently adopted as the reference criterion for evaluating the performance of the PV enhancers.

Table 6. Comparison of PV enhancers using F_{CEE} and $F_{CEE,min}$ when the energy produced from a PV system without an enhancer is increased.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	F_{CEE}	Remark
A	115.00	125.00	30	0.75	0.120	1.240	Not Effective
B	115.00	152.66	32	0.75	0.120	1.033	Not Effective
C	115.00	195.83	35	0.75	0.120	0.826	Effective
D	115.00	204.16	40	0.75	0.120	0.825	Effective

The results indicate that an increase in the energy production of the reference PV system leads to higher F_{CEE} values across all evaluated models. Despite this increase, Models C and D continue to satisfy the effectiveness requirements, recording F_{CEE} values of 0.826 and 0.825, respectively. Since these values remain below 1 while exceeding $F_{CEE,min}$, both models are classified as effective. Conversely, Models A and B produced F_{CEE} values of 1.240 and 1.033, respectively, placing them above the acceptable effectiveness limit and leading to their classification as ineffective.

A comparison with the previous case, in which the reference PV system generated 110 kWh, reveals a decline in the cost–energy effectiveness of all investigated enhancers. This trend can be attributed to the improved performance of the unenhanced PV system, which reduces the relative benefit provided by the enhancement technologies. Consequently, the additional energy generated by the PV enhancers contributes a smaller performance advantage, leading to higher F_{CEE} values. Nevertheless, Models C and D remain capable of generating sufficient additional energy to offset their manufacturing costs and therefore maintain their effective status.

These observations demonstrate that the proposed F_{CEE} metric is highly responsive to variations in the performance of the baseline PV system. As the energy output of the reference PV installation increases, the economic justification for implementing a PV enhancer becomes progressively more demanding. Under such circumstances, larger energy gains are required to compensate for the associated manufacturing costs and preserve favorable cost–energy effectiveness. Therefore, the competitiveness of PV enhancement technology depends not only on its own performance improvement but also on the operating performance of the reference PV system against which it is evaluated.

Compared with the previous scenario in which the reference PV energy output was increased to 115 kWh, the present case with a reduced baseline energy output of 105 kWh resulted in lower F_{CEE} values for all investigated models, thereby improving their economic attractiveness. In the 115 kWh scenario, only Models C and D satisfied the effectiveness criterion, while Models A and B remained ineffective with F_{CEE} values greater than 1. However, when the baseline energy output was reduced to 105 kWh, Model B became effective, with its F_{CEE} value decreasing from 1.033 to 0.967. Similarly, Models C and D exhibited further reductions in F_{CEE} , improving from 0.826 and 0.825 to 0.775 and 0.776, respectively. Although Model A also showed an improvement, its F_{CEE} value remained above the effectiveness threshold. These results demonstrate that the economic viability of PV enhancement technology depends not only on its own energy gain and manufacturing cost but also on the performance level of the reference PV system.

More generally, the combined results from the 105 kWh, 110 kWh, and 115 kWh scenarios indicate that F_{CEE} is positively correlated with the baseline energy output of the unenhanced PV system. As the energy production of the reference PV system increases, the relative contribution of the enhancement technology becomes less significant,

leading to higher F_{CEE} values and reduced cost–energy effectiveness. Conversely, lower-performing reference systems benefit more from the additional energy generated by the enhancement technology, resulting in lower F_{CEE} values and improved economic attractiveness. Therefore, PV enhancement technologies are more likely to achieve favorable F_{CEE} classifications when applied to systems with lower baseline energy yields, whereas high-performing PV systems require proportionally greater energy improvements to justify the additional investment.

3.1.4. The Effect of Changing the One-Unit Electricity Cost of PV on F_{CEE}

Table 7 summarizes the calculated values of F_{CEE} for four hypothetical PV enhancer models under a scenario where the one-unit PV electricity cost is increased from 0.75 to 0.90 \$/kWh. In this analysis, the energy output of the reference PV system was fixed at 110 kWh, whereas the energy outputs of the enhanced PV systems were assumed to be 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The corresponding manufacturing costs of the enhancers were taken as \$30, \$32, \$35, and \$40. The minimum effectiveness threshold, $F_{CEE,min}$, remained constant at 0.115 because its value is determined solely by the energy output of the reference PV system, the operating duration, and the maximum PV power under standard test conditions and is therefore unaffected by changes in electricity pricing.

Table 7. Comparison of PV enhancers using F_{CEE} when the one-unit electricity cost of PV is increased.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	F_{CEE}	Remark
A	110.00	125.00	30	0.90	0.115	1.147	Not Effective
B	110.00	152.66	32	0.90	0.115	0.953	Effective
C	110.00	195.83	35	0.90	0.115	0.760	Effective
D	110.00	204.16	40	0.90	0.115	0.756	Effective

The results indicate that a higher PV electricity cost leads to improved cost–energy effectiveness for all evaluated PV enhancer models. This improvement is reflected by a reduction in the calculated F_{CEE} values, which can be attributed to the diminished influence of the cost-related component (Z/U) in the proposed formulation as the unit PV electricity value increases. Consequently, the F_{CEE} values decrease to 1.147, 0.953, 0.760, and 0.756 for Models A, B, C, and D, respectively.

Based on the established effectiveness criteria, Models B, C, and D are classified as effective because their F_{CEE} values fall below the upper limit of 1 while remaining above $F_{CEE,min}$. In contrast, Model A continues to be categorized as ineffective since its F_{CEE} value remains greater than unity despite the increase in PV electricity cost. This outcome suggests that the additional energy generated by Model A is still insufficient to justify its manufacturing cost under the conditions considered.

Among the four configurations, Model D achieved the lowest F_{CEE} value of 0.756, indicating the highest level of cost–energy effectiveness. Model C followed closely with an F_{CEE} value of 0.760, demonstrating a nearly equivalent performance. Although Model B also satisfied the effectiveness criterion, its effectiveness was comparatively lower, reflecting a smaller economic benefit relative to the energy gain achieved.

Overall, these findings demonstrate that the economic value assigned to PV electricity plays a significant role in determining the viability of PV enhancement technologies. As PV electricity cost increases, the monetary benefit associated with additional energy generation becomes more substantial, thereby improving the attractiveness of PV enhancers. This effect is particularly pronounced for systems capable of delivering considerable energy

gains, highlighting the importance of both energy performance and PV electricity cost when assessing the cost–energy effectiveness of PV enhancement strategies.

Compared with the previous scenario involving higher PV electricity costs, the calculated F_{CEE} values are evaluated for the same PV enhancer models under a scenario in which the one-unit PV electricity cost is reduced to 0.50 \$/kWh. The assessment was conducted using a baseline PV energy output of 110 kWh, while the enhanced PV systems were assumed to generate 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The corresponding manufacturing costs of the enhancers were \$30, \$32, \$35, and \$40. Under these conditions, the minimum effectiveness threshold, $F_{CEE,min}$, remained unchanged at 0.115 because it depends solely on the reference PV system performance, operating duration, and maximum power output under standard test conditions and is therefore independent of the PV electricity cost.

The results show that reducing the one-unit PV electricity cost adversely affects the cost–energy effectiveness of the investigated PV enhancers. As the PV electricity value decreases, the cost-related term (Z/U) becomes more dominant in the F_{CEE} formulation, leading to higher F_{CEE} values for all configurations. Consequently, Models A and B produced F_{CEE} values of 1.360 and 1.140, respectively, exceeding the effectiveness threshold and therefore being classified as ineffective.

In contrast, Models C and D continued to satisfy the effectiveness criterion, yielding F_{CEE} values of 0.919 and 0.931, respectively. Since both values remain below the upper effectiveness limit of 1 while exceeding $F_{CEE,min}$, these configurations are classified as effective. Among all investigated models, Model C achieved the lowest F_{CEE} value and therefore exhibited the highest cost–energy effectiveness, whereas Model D demonstrated slightly lower economic performance despite maintaining an effective classification.

Compared with the previous scenario in which the one-unit PV electricity cost was increased to 0.90 \$/kWh, the present case produced higher F_{CEE} values for all investigated models. Under the higher PV electricity-cost scenario, Models B, C, and D were classified as effective, whereas in the current scenario, Model B became ineffective as its F_{CEE} value increased above the effectiveness threshold. Similarly, Models C and D experienced noticeable increases in F_{CEE} , indicating a reduction in their economic attractiveness. These results demonstrate that the economic value assigned to the generated PV electricity plays a critical role in determining the cost–energy effectiveness of PV enhancement technologies.

More generally, the combined results from the low-, baseline-, and high-electricity-cost scenarios reveal that F_{CEE} is inversely related to the unit value of PV electricity. Higher PV electricity values increase the economic benefit associated with the additional energy generated by the enhancement technology, thereby reducing F_{CEE} and improving cost–energy effectiveness. Conversely, lower electricity values diminish the financial return from energy production and increase the relative impact of manufacturing cost, leading to higher F_{CEE} values. Therefore, PV enhancement technologies are more likely to achieve favorable economic performance in regions or applications where the value of generated electricity is relatively high, whereas larger energy gains are required to justify enhancement costs under low electricity-price conditions.

3.1.5. The Effect of Changing the Manufacturing Cost of a PV Enhancer on F_{CEE}

Table 8 summarizes the calculated values of the proposed F_{CEE} for four hypothetical PV enhancer models under a scenario where the manufacturing costs of the enhancers are increased while all other parameters remain unchanged. The reference PV system was assumed to generate 110 kWh of energy without enhancement, whereas the enhanced PV systems produced 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The manufacturing costs of the enhancers were increased to \$35, \$36, \$37, and \$41

for Models A, B, C, and D, respectively, while the unit cost of PV electricity was maintained at 0.75 \$/kWh. The minimum effectiveness threshold, $F_{CEE,min}$, remained constant at 0.115 because it is independent of the manufacturing cost and is governed solely by the reference PV system performance, operating duration, and maximum power output under standard test conditions.

Table 8. Comparison of PV enhancers using F_{CEE} when the manufacturing cost of a PV enhancer is increased.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	F_{CEE}	Remark
A	110.00	125.00	35	0.75	0.115	1.253	Not Effective
B	110.00	152.66	36	0.75	0.115	1.035	Not Effective
C	110.00	195.83	37	0.75	0.115	0.814	Effective
D	110.00	204.16	41	0.75	0.115	0.807	Effective

The results show that an increase in manufacturing cost leads to a corresponding increase in the calculated F_{CEE} values for all evaluated models. This trend is expected because a higher manufacturing cost increases the magnitude of the economic term (Z/U) within the proposed formulation, thereby reducing the overall cost–energy attractiveness of the PV enhancers. As a result, Models A and B recorded F_{CEE} values of 1.253 and 1.035, respectively. Since both values exceed the upper effectiveness limit of 1, these configurations are classified as ineffective under the specified conditions.

In contrast, Models C and D maintained F_{CEE} values below unity, with values of 0.814 and 0.807, respectively, and therefore continued to satisfy the effectiveness criterion. Among the four configurations, Model D achieved the lowest F_{CEE} value despite possessing the highest manufacturing cost. This outcome highlights the importance of energy yield in determining cost–energy effectiveness, as the substantial increase in energy production provided by Model D was sufficient to offset its higher implementation cost. Model C also demonstrated strong performance, indicating that its energy gain remained economically favorable even after the increase in manufacturing cost.

Relative to the baseline cost scenario, all models experienced a reduction in cost–energy effectiveness as manufacturing costs increased. However, the magnitude of this reduction varied among the models. The deterioration was more pronounced for Models A and B, whose relatively modest energy gains were unable to compensate for the higher investment cost. Conversely, Models C and D exhibited greater resilience to cost increases because of their superior energy generation capabilities.

Overall, these results confirm that the proposed F_{CEE} indicator is highly responsive to changes in economic parameters and provides a practical means of quantifying the balance between additional energy production and implementation cost. The findings further suggest that PV enhancement technologies with substantial energy gains can remain economically attractive even when manufacturing costs increase, whereas technologies offering limited performance improvements are considerably more vulnerable to cost escalation.

Compared with the previous scenario involving higher PV enhancer manufacturing costs, the calculated F_{CEE} values were evaluated for four hypothetical PV enhancer models under a scenario in which the manufacturing costs of the PV enhancers were reduced while all other parameters remained unchanged. The reference PV system without enhancement was assumed to generate 110 kWh of energy, whereas the enhanced PV systems produced 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The manufacturing costs were reduced to \$20, \$21, \$22, and \$23 for Models A, B, C, and D, respectively, while the unit PV electricity value remained at 0.75 \$/kWh. Under these

conditions, $F_{CEE,min}$ remained unchanged at 0.115 and was used as the benchmark for performance evaluation.

The results demonstrate that reducing the manufacturing cost significantly improves the cost–energy effectiveness of the investigated PV enhancers. The calculated F_{CEE} values decreased to 1.093, 0.904, 0.711, and 0.689 for Models A, B, C, and D, respectively. Consequently, Models B, C, and D satisfied the effectiveness criterion and were classified as effective, whereas Model A remained ineffective because its F_{CEE} value exceeded unity. Among all evaluated configurations, Model D achieved the lowest F_{CEE} value, indicating the highest cost–energy effectiveness, followed by Models C and B.

Compared with the previous case in which higher manufacturing costs were considered (\$35, \$36, \$37, and \$41 for Models A, B, C, and D, respectively), all models exhibited lower F_{CEE} values and improved economic performance. In the higher-cost scenario, only Models C and D satisfied the effectiveness criterion, whereas Model B remained ineffective with an F_{CEE} value above unity. Following the reduction in manufacturing costs, Model B became effective, while Models C and D experienced further improvements in their F_{CEE} values. These results clearly demonstrate the strong influence of manufacturing cost on the economic viability of PV enhancement technologies.

More generally, the combined results from the low-, baseline-, and high-cost scenarios indicate that F_{CEE} is directly related to the manufacturing cost of the enhancement technology. As the manufacturing cost increases, the cost-related component of the proposed metric becomes more dominant, resulting in higher F_{CEE} values and reduced cost–energy effectiveness. Conversely, lowering the manufacturing cost reduces the economic burden associated with the enhancement technology and improves its ability to generate additional energy at a justifiable cost. Therefore, cost reduction is an effective strategy for improving the economic attractiveness of PV enhancement technologies, particularly for configurations that already provide moderate energy gains. These findings further confirm that the proposed F_{CEE} indicator is highly sensitive to manufacturing cost and can serve as a useful tool for comparing alternative PV enhancement technologies from both economic and energy-performance perspectives.

3.1.6. The Effect of Changing $P_{out,max}$ on F_{CEE}

Table 9 presents the calculated values of the proposed F_{CEE} for PV enhancer models under a scenario where the maximum output power of the enhanced PV system under standard test conditions is increased from 120 W to 150 W. In this analysis, the reference PV system was assumed to generate 110 kWh of energy without enhancement, while the enhanced systems produced 125, 152.66, 195.83, and 204.16 kWh for Models A, B, C, and D, respectively. The manufacturing costs of the PV enhancers were maintained at \$30, \$32, \$35, and \$40, respectively, whereas the unit cost of PV electricity was fixed at 0.75 \$/kWh.

Table 9. Comparison of PV enhancers using F_{CEE} when $P_{PVE,outmax}$ is increased.

Model	$E_{PV,out}$ (kWh)	$E_{PVE,out}$ (kWh)	Z (\$)	U (\$/kWh)	$F_{CEE,min}$	$F_{CEE,min}$	Remark
A	110.00	125.00	30	0.75	0.092	1.200	Not Effective
B	110.00	152.66	32	0.75	0.092	1.000	Neutral
C	110.00	195.83	35	0.75	0.092	0.800	Effective
D	110.00	204.16	40	0.75	0.092	0.800	Effective

The results indicate that increasing the maximum achievable power output influences only the minimum effectiveness threshold, $F_{CEE,min}$, which decreases from 0.115 to 0.092. This reduction is expected because the minimum effectiveness factor is

inversely related to the maximum output power of the enhanced PV system. Therefore, a higher value of $P_{PVE,outmax}$ lowers the theoretical minimum limit that can be attained by the proposed indicator. In contrast, the calculated F_{CEE} values remain unchanged at 1.200, 1.000, 0.800, and 0.800 for Models A, B, C, and D, respectively. This behavior occurs because the F_{CEE} formulation is governed by the actual energy output of PV systems, the manufacturing cost of the enhancers, and the unit value of PV electricity, none of which were altered in this scenario.

Based on the established classification framework, Models C and D continue to satisfy the effectiveness criterion, as their F_{CEE} values remain below 1 while exceeding the minimum benchmark value. These results indicate that both configurations provide sufficient additional energy generation to justify their associated implementation costs. Model B occupies a neutral position, with an F_{CEE} value exactly equal to 1, suggesting that the economic value of the additional energy produced is approximately equivalent to the manufacturing cost of the enhancer. Conversely, Model A remains ineffective because its F_{CEE} value exceeds the upper effectiveness limit, indicating an unfavorable balance between energy gain and investment cost.

Among the evaluated configurations, Models C and D exhibit the strongest cost–energy performance and maintain their positions as the most effective alternatives. Their low F_{CEE} values reflect a favorable combination of substantial energy enhancement and acceptable manufacturing cost, resulting in superior economic viability relative to the other models.

Overall, the findings demonstrate that increasing the maximum output power of the enhanced PV system primarily affects the theoretical lower bound of the proposed indicator rather than its calculated value. As a result, the minimum benchmark becomes more stringent, while the relative ranking and effectiveness classification of the PV enhancer models remain unchanged. This observation highlights the role of $P_{PVE,outmax}$ as a parameter that defines the ideal performance limit of the F_{CEE} metric, whereas the actual effectiveness of a PV enhancer continues to be determined by its realized energy gains and associated economic costs.

Compared with the previous scenario in which the maximum output power of the enhanced PV system under standard test conditions was increased from 120 W to 150 W, the present case with a reduced maximum power output of 115 W produced identical F_{CEE} values and effectiveness classifications. In the 150 W scenario, $F_{CEE,min}$ decreased to 0.092, whereas in the present case it increased to 0.120. Despite this variation in the benchmark value, the calculated F_{CEE} values remained unchanged at 1.200, 1.000, 0.800, and 0.800 for Models A, B, C, and D, respectively. Consequently, Models C and D remained effective, Model B remained neutral, and Model A remained ineffective. This consistency demonstrates that changes in $P_{PVE,outmax}$ do not directly influence the economic evaluation of the PV enhancers but only modify the theoretical lower benchmark of the proposed indicator.

More generally, the combined results from the 115 W, 120 W, and 150 W scenarios indicate that $P_{PVE,outmax}$ has the weakest influence among all investigated sensitivity parameters. Unlike manufacturing cost, PV electricity value, baseline energy output, and enhanced energy generation, variations in $P_{PVE,outmax}$ do not affect the calculated F_{CEE} values because this parameter does not appear directly in the F_{CEE} equation. Instead, it influences only the minimum effectiveness benchmark, $F_{CEE,min}$, which serves as a theoretical reference for evaluating the performance potential of PV enhancement technologies. Therefore, while increasing $P_{PVE,outmax}$ lowers the theoretical minimum benchmark and decreasing it raises the benchmark, the actual cost–energy effectiveness and ranking of the evaluated technologies remain unchanged. This finding confirms that the proposed F_{CEE}

metric primarily evaluates practical economic and energy performance rather than theoretical maximum power capability.

3.1.7. Overall Impact of Key Parameters on F_{CEE}

The collective sensitivity analyses reveal that F_{CEE} is fundamentally controlled by the trade-off between enhancement cost and additional energy generation. Parameters that increase the energy benefit, particularly higher $E_{PVE,out}$ values, consistently reduce F_{CEE} and improve cost-effectiveness. Similarly, higher PV electricity values (U) decrease the economic burden associated with the enhancement cost term (Z/U), resulting in lower F_{CEE} values. In contrast, increasing enhancement cost (Z) or reducing the additional energy generated by the enhancement technology increases F_{CEE} and may shift the system from a cost-effective classification ($F_{CEE} < 1$) to a non-cost-effective classification ($F_{CEE} > 1$). Among the investigated parameters, $E_{PVE,out}$ and Z exhibit the strongest influence on F_{CEE} , indicating that maximizing energy gain while minimizing enhancement cost is critical for achieving favorable economic performance. Overall, the sensitivity analyses demonstrate that the proposed metric responds consistently to economically meaningful parameter variations and provides a rational basis for preliminary screening of PV enhancement technologies.

3.2. Comparison Between the Existing and the New Assessment Method for PV Enhancers

Table 10 compares the characteristics of the previously proposed F_{CE} and the newly developed F_{CEE} . Although both indicators integrate the manufacturing cost of the PV enhancer into the performance evaluation process, they differ in the performance metric employed. The F_{CE} indicator is based on instantaneous power output and is therefore more suitable for short-term experimental investigations and laboratory-scale assessments. In contrast, F_{CEE} utilizes cumulative energy generation, enabling a more comprehensive evaluation of long-term operational and economic performance. Consequently, F_{CEE} captures the actual energy benefits delivered by PV enhancement technologies over extended operating periods and provides a more realistic assessment of their economic viability. Furthermore, the proposed F_{CEE} has been validated using data obtained from real photovoltaic cooling systems, demonstrating its applicability under practical operating conditions and confirming its suitability for real-world PV enhancement applications.

Table 10. Comparison between the existing and the new assessment methods.

Aspect	F_{CE}	F_{CEE}
Full Name	Cost Effectiveness Factor	Cost–Energy Effectiveness Factor
Primary Objective	Evaluate effectiveness based on cost and power output	Evaluate effectiveness based on cost and energy output
Output Basis	Power (W)	Energy (kWh)
Time Consideration	Not explicitly included	Implicitly included through accumulated energy generation
Electricity Cost Parameter	Unit PV power cost (Y)	Unit PV electricity cost (U)
Performance Metric	Instantaneous performance	Long-term energy performance
Suitable For	Laboratory experiments and short-term testing	Long-term operational and economic assessment
Sensitivity	Sensitive to momentary power fluctuations	Sensitive to cumulative energy production
Data Requirement	Power measurements	Energy production measurements
Economic Perspective	Short-term cost–performance evaluation	Long-term cost–energy evaluation

3.3. Relationship Between F_{CEE} and Established Economic Assessment Methods

The proposed F_{CEE} is intended to complement, rather than replace, established economic assessment approaches such as Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Electricity (LCOE), and Lifecycle Cost Analysis (LCCA). These methods are widely recognized for evaluating the economic feasibility and financial performance of photovoltaic systems because they incorporate a broad range of economic variables, including capital investment, operation and maintenance costs, discount rates, inflation, financing conditions, project lifetime, and electricity tariffs (see Table 11). As a result, they provide comprehensive assessments of project profitability and economic viability.

Table 11. Comparison of F_{CEE} with established economic assessment methods.

Aspect	F_{CEE}	LCOE	NPV	IRR	LCCA
Purpose	Technology screening	Cost of electricity	Profitability	Return on investment	Lifecycle cost
Main Output	Dimensionless factor	\$/kWh	Monetary value	%	Monetary value
Data Requirement	Low	High	High	High	High
Suitable for Early Technology Assessment	Yes	Limited	No	No	Limited
Includes Discount Rate	No	Usually Yes	Yes	Yes	Sometimes
Includes O&M Costs	No	Yes	Yes	Yes	Yes
Includes Financing Conditions	No	Yes	Yes	Yes	No
Applicable to Experimental Studies	High	Moderate	Low	Low	Moderate
Primary Role	Preliminary screening	Economic evaluation	Investment decision	Investment decision	Cost assessment
Assessment Level	Technology-level	Project-level	Project-level	Project-level	Project-level

In contrast, F_{CEE} was developed to address a different objective. The indicator focuses specifically on evaluating photovoltaic enhancement technologies by integrating energy generation and manufacturing cost into a single dimensionless metric. Unlike NPV, IRR, LCOE, and LCCA, the proposed method requires only a limited number of parameters that are commonly reported in experimental and field studies, namely the energy output of the PV system with and without an enhancer, the manufacturing cost of the enhancer, and the unit value of PV electricity. Consequently, F_{CEE} can be applied during the early stages of technology development when detailed economic information is often unavailable.

Another important distinction is that NPV, IRR, LCOE, and LCCA are generally project-level assessment tools, whereas F_{CEE} is primarily a technology-level assessment tool. The proposed factor enables rapid comparison of different PV enhancement technologies, such as cooling systems, reflectors, and tracking mechanisms, using a consistent framework based on energy performance and cost. This characteristic is particularly useful because many PV cooling and enhancement studies report improvements in energy generation (kWh) and manufacturing costs but do not provide sufficient information to perform comprehensive NPV, IRR, LCOE, or lifecycle cost analyses. Furthermore, the proposed indicator can serve as a preliminary screening tool before conducting more detailed techno-economic evaluations. Technologies exhibiting unfavorable F_{CEE} values may be excluded from further consideration, whereas technologies demonstrating favorable cost-energy performance can subsequently be subjected to comprehensive economic analyses using NPV, IRR, LCOE, or LCCA. Therefore, F_{CEE} should be viewed as a complementary indicator that bridges the gap between technical performance assessment and detailed economic evaluation. It should be noted that no universal quantitative relationship exists

between F_{CEE} and conventional economic indicators such as LCOE, NPV, or IRR because these metrics depend on numerous project-specific financial and operational parameters. Therefore, F_{CEE} is intended as a preliminary screening indicator rather than a replacement for comprehensive economic assessment methods. In general, $F_{CEE} < 1$ suggests that the additional energy benefit generated by the enhancement technology is sufficient to justify its manufacturing cost under the assumed electricity value, indicating potential economic viability and suitability for further detailed evaluation. Conversely, $F_{CEE} > 1$ indicates a lower likelihood of favorable economic performance, while $F_{CEE} = 1$ represents the break-even condition. The relationship among these assessment methods can be summarized as follows: F_{CEE} provides a rapid technology-level evaluation based on energy generation and manufacturing cost, while NPV, IRR, LCOE, and LCCA provide comprehensive project-level economic assessments. Accordingly, the proposed factor is most suitable for the preliminary evaluation, comparison, and ranking of PV enhancement technologies, whereas final investment and deployment decisions should be based on detailed techno-economic analyses that incorporate lifecycle costs, financing conditions, discount rates, operational expenses, and project-specific economic factors.

3.4. Future Work

Several directions for future work are identified as follows:

1. The current F_{CEE} framework focuses on the effectiveness of PV enhancement technologies based on energy generation and manufacturing cost. Future studies may extend the methodology by incorporating system-level factors such as MPPT efficiency, inverter performance, energy storage coordination, grid interaction, and power management strategies to develop a more comprehensive PV system effectiveness assessment framework.
2. Future work should incorporate uncertainty analysis, probabilistic sensitivity analysis, and error propagation techniques when sufficient experimental uncertainty information becomes available. Such analyses would provide additional insight into the confidence bounds and statistical robustness of the proposed indicator.
3. Future research should investigate the incorporation of lifecycle costs, maintenance expenses, discount rates, component degradation, replacement costs, and financing considerations to develop a more comprehensive economic effectiveness indicator for photovoltaic enhancement technologies.
4. Future research should investigate correlations between F_{CEE} and established economic indicators such as LCOE, NPV, and IRR using large datasets from diverse PV enhancement technologies to establish empirical interpretation ranges for F_{CEE} .

4. Conclusions

This study proposed a novel Cost–Energy Effectiveness Factor (F_{CEE}) for evaluating the economic effectiveness of photovoltaic (PV) enhancement technologies. Unlike conventional power-based effectiveness indicators, the proposed methodology employs cumulative energy generation as the primary performance metric, thereby providing an assessment framework that is more closely aligned with the fundamental objective of photovoltaic systems, namely long-term electricity generation. The proposed F_{CEE} integrates enhanced PV energy output, reference PV energy output, manufacturing cost, and electricity value into a single dimensionless indicator that enables straightforward comparison of different PV enhancement technologies. In addition, a minimum effectiveness benchmark, $F_{CEE,min}$, was introduced to establish a reference criterion for effectiveness evaluation. The results demonstrated that F_{CEE} responds consistently to variations in key technical and economic parameters, including energy generation, manufacturing cost, electricity

price, and maximum system output power. The sensitivity analysis further showed that increased energy generation improves effectiveness, whereas higher manufacturing costs generally reduce economic attractiveness.

To demonstrate the applicability of the proposed methodology, F_{CEE} was applied to multiple experimentally derived datasets obtained from published photovoltaic enhancement studies as well as to an independent outdoor PV cooling experiment conducted by the authors under actual Malaysian climatic conditions. The successful application of the indicator across different technologies and operating conditions confirmed its robustness, practicality, and suitability for comparative assessment purposes. The results indicate that F_{CEE} can effectively distinguish between enhancement technologies with different cost–performance characteristics while maintaining a simple and transparent evaluation procedure and hence promoting the efficient utilization of sustainable energy resources.

From a broader perspective, the principal contribution of this work lies in establishing an energy-based economic assessment framework for photovoltaic enhancement technologies. Although the proposed methodology builds upon the conceptual foundation of previously developed effectiveness indicators, the transition from instantaneous power evaluation to cumulative energy assessment expands the applicability of effectiveness analysis to long-term operational performance. This shift is particularly important because the economic viability of PV enhancement technologies is ultimately determined by their contribution to energy generation rather than by instantaneous power output alone. Nevertheless, the present study has several limitations. The current formulation does not explicitly incorporate lifecycle costs, maintenance expenses, discount rates, financing structures, component degradation, inflation, or other advanced economic parameters that are commonly considered in comprehensive techno-economic analyses. Furthermore, the sensitivity analysis was conducted using a deterministic approach and did not include uncertainty quantification or probabilistic error propagation. Consequently, F_{CEE} should be viewed as a preliminary engineering assessment and screening tool that complements, rather than replaces, detailed economic evaluation methods such as life-cycle cost analysis, levelized cost of energy analysis, net present value analysis, and discounted cash flow approaches.

Future research should focus on extending the proposed framework by incorporating lifecycle economic parameters, uncertainty analysis, degradation effects, maintenance costs, and financing considerations. Additional validation using long-term field measurements and commercial-scale photovoltaic installations is also recommended. Furthermore, the development of integrated effectiveness indicators that simultaneously account for energy performance, cost, lifespan, environmental impact, and sustainability considerations represents a promising direction for future investigation.

Overall, the proposed F_{CEE} provides a practical, transparent, and energy-oriented framework for evaluating photovoltaic enhancement technologies and thereby promoting sustainable energy resources. The methodology offers researchers, engineers, and technology developers a useful tool for preliminary comparative assessment and contributes toward the ongoing development of standardized evaluation approaches for photovoltaic enhancement systems.

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Abbreviations

Nomenclature

F	factor (dimensionless)
P	power (W)
PV	photovoltaic module
PVE	photovoltaic module with an enhancer
RM	Malaysian Ringgit
U	cost of one unit of PV electricity
Z	manufacturing cost of PV enhancer

Subscript

CEE	cost and energy effectiveness
out	output
outmax	maximum output
STC	PV standard test conditions

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