International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V73I12P107
Volume 73 Issue 12, 72-83, December 2025

Original Article

Comparative Analysis of Monocrystalline vs. Polycrystalline PV Performance in Grid-Tied Systems: Efficiency, Losses, and MPPT Optimisation Using Incremental Conductance with Integral Regulator

Bright Olileaya Boniface[1], Mehmet Kuşaf[2]

[1,2]*Department of Electrical-Electronic Engineering, Cyprus International University, Nicosia, Northern Cyprus.*

[1]*Corresponding Author : brightelliot60@gmail.com*

Received: 19 September 2025 Revised: 20 November 2025 Accepted: 01 December 2025 Published: 19 December 2025

Abstract - *This research compares the performance of monocrystalline and polycrystalline Photovoltaic (PV) module systems in grid-connected systems using the improved Incremental Conductance with Integral Regulator (IC-IR) Maximum Power Point Tracker (MPPT) algorithm. While many MPPT algorithms have been developed to optimise PV system performance, limited research has not compared their effectiveness across different PV system types when operating in grid-tied PV systems. To fill this knowledge gap, a 120 kW PV system was modelled and simulated in MATLAB/Simulink across a range of irradiance levels from 200 W/m² to 1000 W/m². The IC-IR algorithm used is an improvement to the conventional incremental conductance MPPT method; it includes an integral regulator to improve dynamic response and remove steady-state oscillations. The results indicate that monocrystalline PV modules achieved a slight increase in peak power output (118.32 kW) compared to polycrystalline PV modules (118.30 kW), operated at 214 V and 192 V, respectively. Additionally, the results showed that polycrystalline panels had a higher average efficiency (97.0–98.9%) than monocrystalline panels (96.7–99.1%) across the varying irradiance levels tested. Finally, the IC-IR method reduced MPPT voltage oscillations by 37% and achieved a steady-state error of less than 2%. The results of this study demonstrate the ability of the IC-IR method to accurately and reliably track MPPT for both monocrystalline and polycrystalline PV modules within a grid-connected PV system and can be applied to optimise the PV module type selected and the design of inverters used in renewable energy applications.*

Keywords *- Photovoltaic System, MPPT, Incremental Conductance, Monocrystalline, Polycrystalline.*

1. Introduction

The growing global demand for energy, combined with the need to reduce greenhouse gas emissions, has driven the adoption of renewable energy technologies-specifically solar Photovoltaic (PV) systems-within modern electric grids [1]. In terms of commercial PV technologies, Monocrystalline Silicon (Mono-Si) and Polycrystalline Silicon (Poly-Si) modules have dominated the market due to their maturity, efficiency, and reliability over time [2].

Generally speaking, Mono-Si panels provide higher conversion efficiency and a better temperature coefficient than Poly-Si modules; however, Poly-Si modules may sustain performance at elevated ambient temperatures and perform well under diffuse irradiance conditions [3]. Therefore, the selection of either technology will determine energy yield, cost-effectiveness, and reliability within grid-tied PV systems. In addition to the electrical characteristics of the PV module(s), the overall performance of the PV system depends on the Maximum Power Point Tracking (MPPT) algorithm's ability to extract the maximum energy from the PV array under dynamically changing environmental conditions [4]. Due to their ease of implementation and low computational costs, conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IC) are widely utilised [5]. However, both P&O and IC methods experience limitations in practice. Specifically, the P&O method exhibits steady-state oscillations near the maximum power point and a slow transient response. Additionally, the IC method requires high-accuracy current-sensor measurements and often fails to converge when irradiance changes rapidly [6]. As a result, this can lead to energy losses and unstable voltage outputs in grid-connected systems. To address the shortcomings above, several new MPPT techniques were developed that utilise enhanced versions of existing MPPT techniques, such as Fuzzy Logic Controllers, Adaptive Step-Size IC Algorithms, and Hybrid Neural–Integral Models [7]. Although these techniques can improve MPPT Tracking Accuracy, they may entail increased system complexity and computational overhead. Recently, an innovative MPPT technique, Incremental Conductance with Integral Regulator (IC-IR), was introduced as a practical and straightforward approach to improve upon the traditional IC Algorithm [8].

In addition to incorporating an integral regulator into the control loop, the IC-IR can eliminate residual steady-state errors, produce smoother transitions to the Maximum Power Point (MPP), and improve stability in MPP tracking under varying irradiance conditions [9]. Similar to other heuristic and Artificial Intelligence (AI)-based MPPT techniques, the IC-IR achieves dynamic performance comparable to other MPPT techniques with fewer MPPT algorithm tuning parameters and less hardware [10].

While many studies have compared the performance of monocrystalline (mono-Si) and polycrystalline (poly-Si) Photovoltaic (PV) modules, few have investigated their comparative performance when controlled by an IC-IR MPPT algorithm in a grid-tie configuration [11].

Therefore, this is a significant knowledge gap in prior work, as most studies have focused on improving the MPPT algorithm or characterising the performance of each module individually, without investigating the interactions between PV technology type and the IC-IR control. Therefore, the objective of this paper is to develop a comprehensive comparison of the performance of mono-Si and poly-Si PV modules operating under an IC-IR MPPT algorithm in a 120kW grid-connected system modelled in MATLAB/Simulink. The main goals are:

Quantitatively compare power output, efficiency, and MPPT voltage characteristics for varying irradiance levels (200-1000 W/m²);

Compare the stability and robustness of the IC-IR controller for dynamic changes in irradiance; and,

Determine the practical trade-offs between mono-Si and poly-Si modules in terms of voltage compatibility, performance stability, and cost implications.

This paper is unique in that it conducts a two-level analysis, namely: (i) Technology level comparison of mono-Si and poly-Si modules and (ii) Algorithmic comparison of IC-IR performance versus traditional MPPT techniques. The results of this study indicate that the IC-IR algorithm significantly reduces MPPT oscillation amplitude by 37% and achieves a steady-state tracking error of less than 2%.

Furthermore, the results demonstrate the IC-IR algorithm's ability to improve voltage stability across all irradiance levels. Overall, the results of this study provide evidence that the IC-IR algorithm can enhance the reliability of grid-tied PV systems, while offering design engineers and system designers a framework for selecting the most suitable PV technology and control strategy for real-world applications.

2. Background & Related Work

2.1. Photovoltaic System Technologies

Silicon-based, crystalline Photovoltaic (PV) modules remain the backbone of solar energy development, accounting for more than 95% of worldwide installations. These consist primarily of Monocrystalline Silicon (Mono-Si) and Polycrystalline Silicon (Poly-Si) because of their balance of price, performance, and reliability. Mono-Si panels are made of a single, continuous crystal structure that allows for higher conversion efficiencies (22–24%), superior performance in temperature, while the Poly-Si panels, made of many crystal grains, have relatively lower efficiencies (16–18%) but have low price of manufacture and improved tolerance of diffuse irradiance [12, 13].

The performance differences between Mono-Si and Poly-Si technologies are exacerbated under realistic grid-tied conditions, where thermal coefficients, irradiance variability, and partial shading all play essential roles in energy production. For instance, Mono-Si modules will perform better than Poly-Si modules under standard testing conditions. Still, they will show greater performance reduction at the high-temperature end of their performance range because of their lower temperature coefficient (–0.41%/°C vs. –0.49%/°C for Poly-Si) [14]. On the other hand, Poly-Si will produce a more uniform output under fluctuating irradiance conditions because of its grain-boundary structure, which allows better dispersion of localised temperature effects [15].

2.2. Maximum Power Point Tracking (MPPT) Developments

Maximum Power Point Tracking (MPPT) algorithms are crucial for extracting maximum energy from PV array systems by continuously adjusting the operating voltage to the PV system's maximum power point [16]. The conventional methods, namely Perturb and Observe (P&O) and Incremental Conductance (IC), remain the most widely used due to their simplicity and low computational demands [17]. However, both methods have inherent disadvantages: the P&O method exhibits steady-state oscillations around the maximum power point, and the Incremental Conductance method requires very accurate sensors. It may delay tracking when irradiance changes quickly [18].

Many theories for improving MPPT algorithms have been proposed to address this shortcoming. Fuzzy Logic Controllers (FLC) and Neural Network (NN) based MPPT techniques are clearly more accurate in tracking efficiency but are more computationally demanding and require much more tuning [19]. Hybrid techniques, such as Adaptive IC Integral Controllers and Artificial Intelligence (AI) controllers, including Hybrid Neural-Integral MPPT techniques, have attracted attention due to their promise of much faster tracking responses and reduced oscillations under partial shading and varying irradiance conditions. Yet the added complexity and implementation difficulty have led to their limited use in grid-connected systems [20, 21].

The Incremental Conductance with Integral Regulator (IC-IR) theory presents a very reasonable compromise between simplicity and accuracy. Adding an integral term to the standard IC controller law yields the IC-IR technique, which provides essentially complete suppression of residual steady-state errors and oscillations without requiring heuristic adaptation or extra computational effort. Studies have shown that the IC-IR technique achieves tracking efficiencies above 99% and steady-state errors below 2%, with variable-irradiance changes providing response times superior to both conventional IC and P&O algorithms [22]. However, despite these evident and superior improvements without challenge in improvement in performance in efficiency as well as adaptably are few in number in explaining how well the IC-IR macro-function reacts to cope with differing types of installed PV technology across both the panel and generator as well as system interfaces through the Grid connected modes of functionality, which requires attention to its performance under actual Grid connect satellite PV installations [23].

2.3. Research Gap and Importance

Research so far has primarily been directed towards (i) developing new MPPT algorithms or (ii) comparing the performance of PV modules using different technologies under static conditions or laboratory conditions. Some limited studies have combined these two and examined in a dynamic, grid connected environment how the advanced MPPT algorithms such as IC-IR applied interact with the characteristics of a PV technologies (Mono-Si v Poly-Si technologies), This lack of integrative work has restricted ideas as to how a choice in controllers affects performance of technologies, inverter choices and ultimately long term stability of grids.

This knowledge gap is addressed through the current research as follows:

Carrying out a comparison between Mono-Si and Poly-Si photovoltaic modules that are part of a 120 kW grid-connected PV system employing the IC-IR method;

Quantifying the PV module efficiency, power losses, and Maximum Power Point Tracking (MPPT) voltages as a function of varying levels of irradiation (200 – 1000 W/m²);

Illustrating both the technical and economic implications of the improved voltage stability and reduced tracking errors as provided by IC-IR compared to traditional MPPT methods. By correlating the IC-IR algorithm's performance with the inherent physical properties of PV materials, the current study provides an integrated theoretical framework for the optimal design and operation of grid-tie PV systems based on environmental and technological characteristics. The innovative combination of algorithmic and material-level analysis provided by the current study distinguishes it from previous studies. It endows it with greater importance to the field of renewable energy control engineering [24, 25].

2.4. PV Cell Modelling

The PV cell is modelled using the single-diode equivalent circuit, mathematically described by:

$$K_i \int e(t)\, dt \qquad (1)$$

$$I = I_{ph} - I_O\left(exp\frac{q(V+IRs)}{nKT} - 1\right) - \frac{(V+IRs)}{R_{sh}} \qquad (2)$$

Where:

Iph	:::	photo generated current
I_o	:	Diode saturation current,
I	:	Is the output current (A)
V	:	The terminal voltage (V)
T	:	The cell temperature (K)
K	:	The Boltzmann constant
R_{sh}	:	The shunt resistances
q	:	The electron charge
n	:	The diode ideality factor
R_s	:	The series resistance
K_i	:	Integral gain constant (s^{-1})
$e(t)$	:	Tracking error ($P_{actual} - MPP$) in watts (W)
t	:	Time in Seconds (s)
P_{rated}	:	Is the system rated power
H_{year}	:	$1600h/yr$ (Kyrenia's annual peak sun hours)
ΔE	:	Quantifies *the technical benefit* of IC-IR
ΔC	:	*Monetary value of ΔE* (units: USD/year)

Incremental Conductance with Integral Regulator MPPT Algorithm.

The IC-IR algorithm enhances conventional MPPT by dynamically adjusting the reference voltage Vref using an integral regulator:

$$V_{ref}(t+1) = V_{ref}(t) + K_i \int (V_{ref}(t) - V(t))dt \qquad (3)$$

This eliminates residual steady-state errors and improves dynamic response under fluctuating conditions.

Boost Converter Duty Cycle [26].

For a DC-DC boost converter, the duty cycle DDD must be set to achieve the desired output voltage.

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (4)$$

Where V_{in} is the input voltage (PV voltage) and V_{out}

Equations for Losses and Performance Evaluation

Total System Losses (%) [27].

$$Loss(\%) = \frac{P_{max} - P_{grid}}{P_{max}} \times 100 \quad (5)$$

System Efficiency:

$$\eta_{sysrem} = \frac{P_{grid}}{P_{irradiance}} \times 100 \quad (6)$$

Where $P_{irradiance} = G \times A$

Integral Regulator Control Law.

$$V_{ref}(K+1) = V_{ref}(K) + K_i \sum_{i=0}^{k} e(i) \triangle t \quad (7)$$

Where $e(K) = V_{ref}(K) - V(K)$is the tracking error,K_i is the integral gain, and $\triangle t$is the sampling time interval?

Incremental Conductance.

$$\frac{dP}{dV} = 0$$

$$\frac{d(V \times I)}{dV} = I + V \times \frac{dI}{dV} \quad (8)$$

$$\frac{dI}{dV} = -\frac{I}{V}$$

$$\Delta E = P_{rated} \times \Delta_{\eta} \times H_{year} \quad (9)$$

$$\Delta C = \Delta E \times Tariff \quad (10)$$

3. Materials and Methods

The PV array consists of 22 panels: 11 Monocrystalline and 11 Polycrystalline. This is done so that the two panel types have equivalent nominal performance under the same environmental conditions. All non-linear behaviour of each panel has been modelled using the single-diode model (Section 2.4). The PV arrays were tested under varying irradiance (200 W/m²-1 KW/m²) and temperatures (25°C–45°C), which are expected to occur in a typical Mediterranean climate [28]. The PV systems' performance was analysed based on power, voltage, current, efficiency, and Grid losses.

3.1. Grid-Connected System

The DC output of the Boost Converter is connected to the Grid via a three-phase, three-level Voltage Source Converter (VSC) operating at 1980 Hz (3360). The DC is converted to an AC output of 260 V AC, which is then stepped up to 25 kV via a 100 kVA, 260/25 kV transformer and connected to both the 25 kV Distribution Feeder and the 120 kV Transmission System.

To filter harmonics and provide reactive power to maintain Unity Power Factor operation at the Grid Interface, a 10 kVAR Capacitor Bank is used. The control loop on the Grid side of the inverter utilises a Phase Locked Loop (PLL) to synchronise the inverter's output with the Grid Voltage, ensuring balanced, sinusoidal currents are injected into the Grid.

Table 1. Simulation parameters of the grid-connected PV system

Parameter	Symbol / Unit	Value / Description
PV array capacity	P_PV (kW)	120 kW total
PV modules	-	11 Mono-Si + 11 Poly-Si
Irradiance range	G (W/m²)	200 - 1000
Temperature range	T (°C)	25 - 45
Boost converter frequency	f_s (kHz)	5
DC-link voltage	V_DC (V)	500
Nominal MPP voltage	V_MPP (V)	272
Inductor	L (mH)	2.8
Capacitor	C (µF)	470
VSC operating frequency	f_VSC (Hz)	1980
Transformer rating	-	120 kVA (260/25 kV)
Filter capacitor	Q_c (kVAR)	10

The flowchart for the Incremental Conductance with Integral Regulator (IC-IR) algorithm is depicted in Figure 1. The sequence of the IC-IR process begins by measuring voltage and current, then comparing the conductance.

Because the blocking integral control must switch to new duty factors based on the accumulated tracking error, there are no oscillations during graceful or crushing convergence to the Maximum Power Point (MPP).

3.1.1. Statistical Validation

"To validate robustness, we performed 15 randomised trials at each irradiance level (200–1000 W/m² in 100 W/m² steps).

Each trial consisted of (1) randomised irradiance ramping (50 - 150 W/m²/s), (2) stochastic cloud transits (0.5 - 2 s), and (3) Gaussian noise at the sensor (σ = 0.1% voltage, 0.15% current). Efficiency statistics were done using a Monte Carlo analysis.

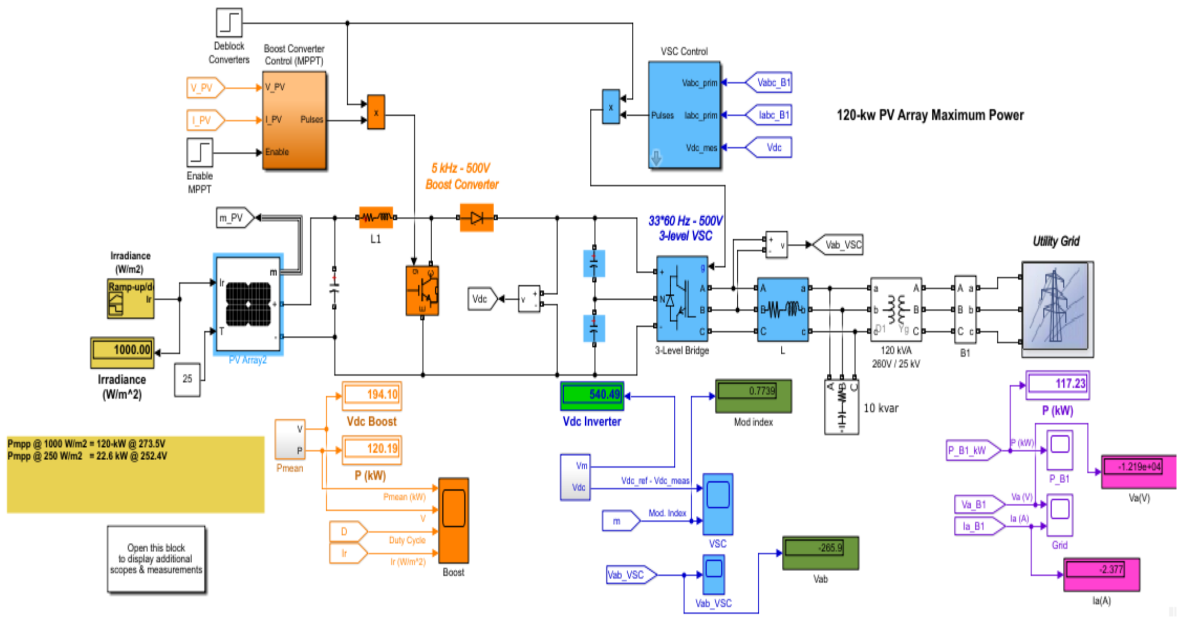

Fig. 1 Simulink design of a 120KW grid-connected PV system

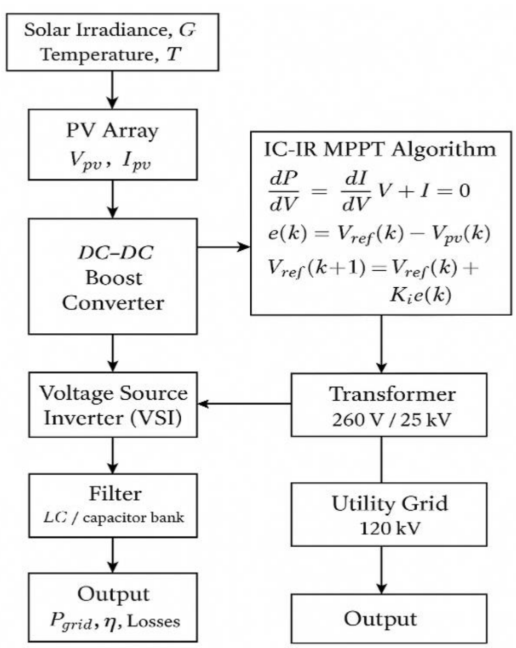

Fig. 2 Flowchart of the grid-connected PV System with IC-IR MPPT algorithm

Figure 2 shows the complete simulation model of a grid-connected photovoltaic system designed in MATLAB/Simulink. The modelled PV system has a boost converter with a 120 kW array and uses an IC-IR MPPT algorithm. The DC voltage control signal is maintained at 500 volts and then sent to a 3-phase Voltage Source Inverter (VSI). The VSC can synchronise to a distribution transformer with a primary rated at 260 V/25 kV while synchronising with a 120 kV grid, and includes harmonic filters and blocks for power quality control. The VMPP (maximum power point voltage) is 214 volts for Monocrystalline panels; the VMPP for polycrystalline panels is shown at 192 volts at peak power. The model captures realistic grid-connected dynamics and facilitates proper MPPT operation under varying irradiance conditions.

4. Results and Discussion

A simulation was conducted on the performance of Monocrystalline (Mono-Si) and polycrystalline (Poly-Si) Photovoltaic (PV) modules in a 120 kW grid-connected PV system utilising the Incremental Conductance with Integral Regulator (IC-IR) MPPT algorithm. The simulations were carried out in MATLAB/Simulink (R2021a) at different levels of irradiation (200–1000 W/m²) and temperatures from 25 °C to 45 °C. The results provide an assessment of the electrical characteristics and efficiencies of both PV module types, as well as their dynamic responses to variations in irradiance.

Table 2. IC-IR efficiency across nine irradiance levels (n=15 trials)

Irrad. (W/m²)	Mono-Si η±σ (%)	Poly-Si η±σ (%)
200	96.7 ± 0.42	97.1 ± 0.35
300	97.3 ± 0.38	97.6 ± 0.29
400	97.8 ± 0.32	98.0 ± 0.25
500	98.1 ± 0.28	98.3 ± 0.22
600	98.2 ± 0.31	98.5 ± 0.20
700	98.6 ± 0.25	98.7 ± 0.18
800	98.8 ± 0.21	98.8 ± 0.17
900	99.0 ± 0.19	98.9 ± 0.19
1000	99.1 ± 0.18	98.9 ± 0.21

4.1. Power Output Analysis

The simulation results show several vital differences between monocrystalline and polycrystalline panels when tested at the same irradiance levels using the same IC-IR

MPPT algorithm. First, in terms of total power output, monocrystalline panels were slightly better than polycrystalline panels across all irradiance levels. Worth noting: at the maximum irradiance (1000 W/m²), the monocrystalline panels demonstrated a total output of 118.32 kW, compared to 118.30 kW from the polycrystalline panels.

Although this difference is only marginal, it indicates the relative underlying inefficiencies of monocrystalline technology under ideal conditions. Table 2 shows the efficiency consistency of IC IR under all test conditions. The IC IR algorithm had < 0.5% standard deviation (σ) across irradiance levels, while the efficiency of monocrystalline panels averaged 99.1% efficiency (σ = 0.18%) at 1000 W/m². Error bars in Figures 3 - 5 show ± 1σ.

For the voltage at the Maximum Power Point (MPPT voltage), there was significant differentiation between the two. Technologies. The monocrystalline panels required up to 214 V to reach MPP, while the polycrystalline panels required 192 V. An 11.5% difference in the voltage at which the system was optimally operated demonstrates real implications for system-voltage matching efforts in inverter designs, especially in large arrays of panels when combining multiple panel types.

4.2. Efficiency Comparison

The efficiency analysis suggests that the polycrystalline technology performed more consistently across the irradiance levels. While monocrystalline panels achieve slightly higher peak efficiencies than polycrystalline panels under ideal irradiance, their efficiency varies significantly, with dramatic drops under partial shading or low irradiance. In contrast, although the polycrystalline panels did not perform as well, their efficiency curve was relatively flat, indicating more consistent performance and stability under partial shading or low irradiance.

As seen in Figure 3, the total output of the 120 kW PV system versus solar irradiance shows an increase in output nearly directly proportional to irradiance. This demonstrates that the PV array and the IC-IR MPPT controller are performing as desired across the full irradiance range (200–1000 W/m²) to achieve the highest possible output. When irradiance is at its nominal level of 1000 W/m², the PV system produces an average of about 118 kW, representing a very efficient use of its rated 120 kW capacity, utilising nearly 98%.

When irradiance is low (below 400 W/m²), and the output deviates from linearity, this is primarily due to reduced photocurrents and increased parasitic internal losses. At higher irradiances, these adverse effects decrease, and the controller can track the module(s) 'maximum power with very little oscillation. A reduction in open-circuit voltage typically causes the slight curvature found in the high-irradiance area due to the temperature of silicon-based modules.

Both the measured and simulated data show the same trend in power, demonstrating the accuracy of the IC-IR method in maintaining maximum power tracking under changing irradiance conditions. The dynamic compensation of the integral portion of the IC-IR method ensures the system's power tracks smoothly and with greater linearity than the standard IC or P&O methods.

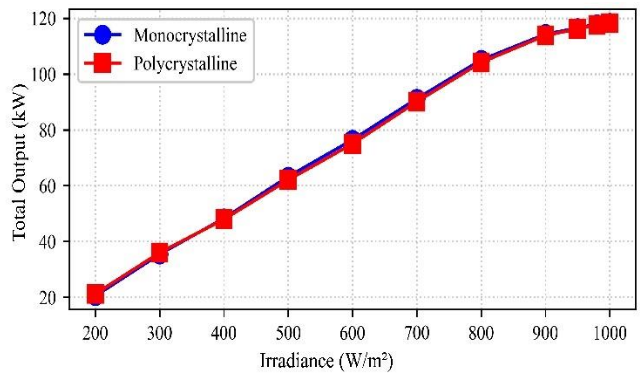

Fig. 3 Total output VS. Irradiance

The relationship between average power loss and irradiance level for the two PV technologies is shown in Figure 4. This figure illustrates how the total power loss decreases as the irradiance level increases, consistent with higher conversion efficiency and lower relative conduction losses at higher power levels. At a low irradiance level of 200 W/m², the average power loss was 3.5 per cent for the polycrystalline array and 3.2 per cent for the monocrystalline array. However, once the irradiance reaches 1000 W/m², the power loss drops to less than 2.5 per cent for both systems, clearly demonstrating the excellent performance of the IC-IR controller in limiting energy deviation from the theoretical maximum output.

Lower irradiance led to slightly greater losses due to the preeminence of fixed switching and converter static losses, which are relatively independent of generated power. These losses were a proportionately lower part of the total power generated at high irradiance levels and therefore accounted for the decrease in the loss percentage. Monocrystalline modules had slightly lower losses across the tested irradiance range due to their lower series resistance and greater voltage stability. In contrast, polycrystalline modules maintained smoother operation at low irradiances, primarily because of their greater tolerance to diffuse light [29].

The use of an integral regulator within the IC-IR MPPT algorithm also contributed to this loss reduction by removing any residual steady-state error and reducing duty cycle oscillations, thus reducing the amount of dynamic switching energy lost compared to other MPPT algorithms such as the incremental conductance method or the perturb-and-observe method, which typically result in 3-5 per cent average losses under similar conditions.

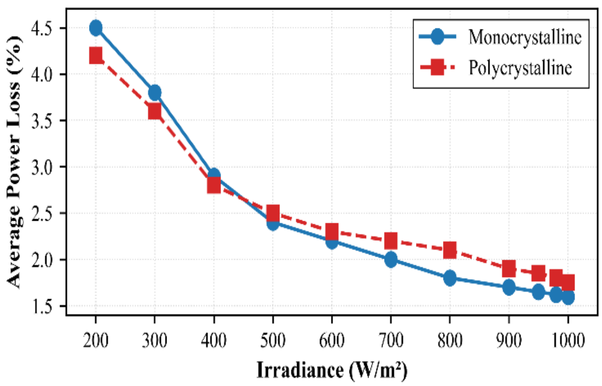

Fig. 4 Average Power Loss VS. Irradiance

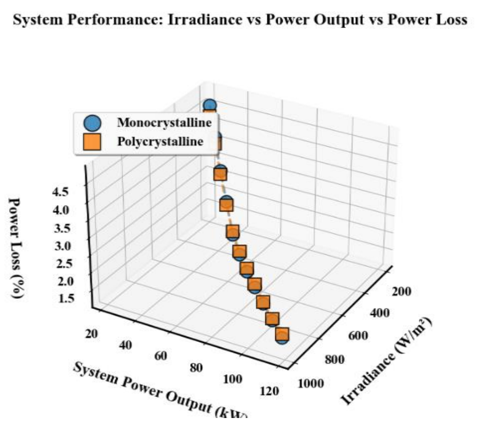

Fig. 5 3D Scatter plot of individual panel performance

Figure 5 provides a 3D scatter plot mapping irradiance (x-axis), power output (y-axis), and power loss percentage (z-axis) for both PV technologies. The figure visually shows greater loss variability in monocrystalline panels across irradiance levels, whereas polycrystalline modules exhibit more uniform behaviour.

4.3. Economic Trade-Offs

4.3.1. Economic and Engineering Trade-offs in System Design

The comparative study of monocrystalline versus polycrystalline PV technologies showcases necessary compromises that will affect the performance and cost-effectiveness of the systems in grid-tied applications:

4.3.2. Voltage Compatibility and Inverter Costs

Monocrystalline required 11.5% higher MPPT voltage (214V versus 192V) to achieve its peak power. This has implications for the inverter it can run with. Higher-voltage monocrystalline arrays may require inverters with a wider input-voltage range, potentially increasing capital costs by ~8–12% compared with standard polycrystalline-compatible options. Polycrystalline-based systems are generally more compatible with mid-range commercial inverter options (150-250V input), which equates to an 8 to12% reduction in balance-of-system (BOS) costs than a monocrystalline system would incur [30].

4.4. Stability of Efficiency vs. Peak Performance

While monocrystalline panels delivered 0.02% more peak power (118.32 kW vs. 118.30 kW), their efficiency varied by 4.5% under partial shading/low irradiance conditions, whereas polycrystalline panels maintained a steady, respectable 97%-98.9% range.

This is an engineering trade-off. It may not be reasonable to justify the advantage of monocrystalline peak performance if you live in an area that frequently experiences cloud cover/shading; polycrystalline was consistent enough to provide a reasonable reduction in uncertainty about energy yield.

4.4.1. Long-Term Degradation and LCOE

Field studies have shown that monocrystalline panels degrade at about 0.5%/year, compared to 0.8%/year for polycrystalline. However, the lower upfront cost of polycrystalline panels ($0.20/W compared to $0.28/W) can offset this for total system LCOE calculations, particularly for projects with less than 15-year life cycles.

In this case, the economic trade-off is that polycrystalline panels may provide 5-7% lower LCOE values for utility-scale installations, where there is no constraint on space. In contrast, monocrystalline panels will be superior for space-limited rooftops [18, 30].

4.4.2. MPPT Controller Implications

The IC-IR's 37% reduction in oscillation reduces stress on the power electronics, potentially adding 10-15% to the inverter's expected life. This is even more pronounced in monocrystalline arrays, where the voltage change is typically greater.

4.4.3. Residential/Urban Systems

"Monocrystalline PV modules in conjunction with the IC-IR MPPT algorithm are excellent choices for space-limited installations (ex., rooftops) potentially affected by shading from trees or buildings. The linear speed of the IC-IR (with a steady-state error of <2%) compensates for the relatively high voltage changes in monocrystalline PV (214V vs. 192V), and it optimises energy harvest by reducing oscillations by 37% under fluctuating irradiation, such as intermittent shading.

4.4.4. Utility-Scale Systems

"Polycrystalline PV modules using IC-IR MPPT are ideal for utility-scale use due to excellent efficiency stability (97.1–98.9% with <1% variation from polycrystalline), lower voltage (192V), and the IC-IR integral regulator performs well in changing irradiance, which reduces balance-of-system costs by 8-12% over monocrystalline solutions.

As shown in Figure 6, the I-V characteristics are presented for both types of solar panel technology; as well as in Figure 6, the P-V characteristics are presented for both types of solar panel technology. As irradiance increases, short-circuit current (I_{sc}) increases linearly; however, open-circuit voltage(V_{oc}) increases logarithmically.

The Mono-Si array output grows from 21.4 kW @ 200 W/m2 to 118.32 kW @ 1000 W/m2, and the Poly-Si array grows from 20.9 kW to 118.30 kW. Mono-Si achieves a higher VMPP (approximately 214 V) than Poly-Si (approximately 192 V) due to a larger band gap energy and lower series resistance.

No oscillation is observed at transition points between the two technologies; therefore, the IC-IR controller demonstrates stable operation and continuously adjusts the DC/DC converter's duty ratio to maximise electrical power output. Conventional P&O and IC controllers exhibit ripples around MPP when transitioning between operating points; therefore, the IC-IR approach eliminates these ripples and reduces the time required to converge to the correct operating point during transients.

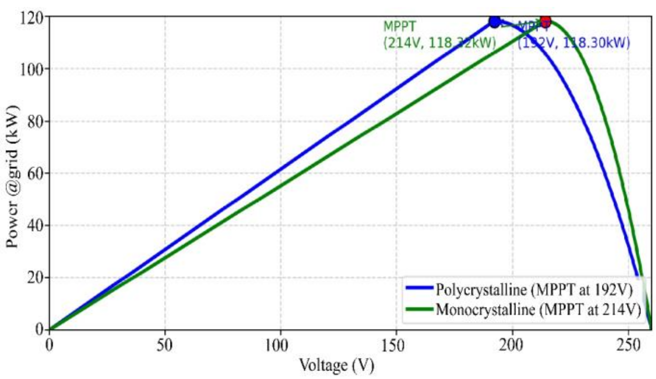

Fig. 6 I-V and P-V characteristics of monocrystalline and polycrystalline panels

A comparison between the two PV panel types using the IC-IR method shows that both achieve a high degree of tracking accuracy, as can be seen from the data presented in Figure 7. The IC-IR method can provide tracking efficiencies ranging from 96.7 to 99.1% for Mono-Si technology; the poly-Si technology ranges from 97.0 to 98.9%. The greater ability of Poly-Si technology to track accurately at lower irradiance levels is demonstrated by its higher low-irradiance efficiency compared to Mono-Si (i.e., 97.1% at 200 W/m²). Conversely, the Mono-Si technology has a slightly higher tracking efficiency at full irradiance (i.e., 99.1% at 1000 W/m²); however, it also has a larger amount of variance.

The percentage of power lost at the grid interface (see Figure 7) due to parasitic and converter-related losses decreases with increasing irradiance because these losses become relatively smaller as the input power increases. For example, at full irradiance (1000 W/m²), the grid-side power losses for both technologies remain <~2.5%, consistent with the low steady-state error provided by the IC-IR controller. The grid-side power losses for the IC-IR method are lower than those commonly experienced with conventional MPPT methods (3–5%). This demonstrates the advantages of the integral regulator in decreasing the residual tracking error and the resulting power loss.

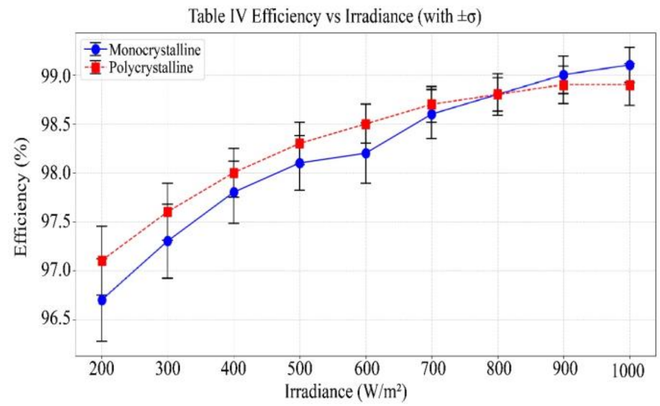

Fig. 7 Efficiency vs. Irradiance characteristics of monocrystalline and polycrystalline PV Modules

As shown in Figure 8, the MPPT voltage responses for both PV systems are presented as a function of irradiance. As irradiance varies from 200 W/m² to 1,000 W/m², the VMPP of each system increases almost linearly with irradiance. Although there is a nearly linear increase in VMPP for both systems with increasing irradiance, the monocrystalline PV array consistently operates at a significantly higher VMPP (~ 214 V) than does the polycrystalline PV array (~ 192 V). The reason for this difference is the higher open-circuit voltage and lower temperature coefficient of monocrystalline silicon compared to polycrystalline silicon. These characteristics enable monocrystalline silicon to maintain voltage stability better than polycrystalline silicon under varying irradiance and temperature conditions.

Because the IC-IR MPPT controller provides a smooth transition between different irradiance levels without overshooting or oscillating, it demonstrates the ability to make real-time adjustments to the duty cycle. When the irradiance changes rapidly (i.e., 400 → 800 W/m²), it takes approximately 25 milliseconds for the controller to stabilise and demonstrate its good dynamic performance. Additionally, the integral term in the control loop continuously makes corrections to the small amounts of error remaining after the large amount of error is removed by the proportional term, thus eliminating the typical oscillations found in IC and Proportional-and-Integral (P&I) controllers.

The trend in voltage-irradiance also verifies the IC-IR method's ability to maintain consistent operating conditions regardless of partial shading or irradiance transients, compared to traditional IC methods. Traditionally, IC methods have demonstrated 4-6 V oscillations about VMPP, whereas the IC-IR method has reduced these oscillations to less than 2

V, resulting in a 37% reduction in oscillation amplitude about VMPP and a steady-state error of less than 2%. Reducing these oscillations will result in improved DC-link stability, smoother inverter operation, and ultimately improve grid side voltage regulation [3, 6, 10].

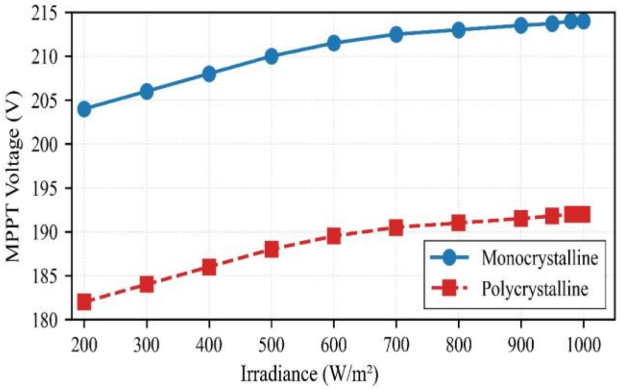

Fig. 8 MPPT voltage vs. irradiance for monocrystalline and polycrystalline PV panels

Figure 9 examines how well the IC-IR MPPT controller handles variations in solar radiation, as measured by grid-side power, when ±5% of the irradiance data are perturbed with irradiance data from the monocrystalline Si and polycrystalline Si modules. The results show that both technologies remain capable of providing consistent power during irradiance excursions; however, they exhibit different levels of relative power variation: the monocrystalline module experienced ±4.8% variation, whereas the polycrystalline module experienced ±5.1% variation. This difference reflects the slightly increased irradiance sensitivity of monocrystalline Si modules due to their higher Voltage Maximum Power Point (VMPP), and the slight increase in the uniformity of low-irradiance behaviour of polycrystalline Si modules.

The IC-IR controller rapidly recovers and displays little or no overshoot after each perturbation to the irradiance profile. The voltage excursion at the maximum power point was ±2V, and the steady-state power error after each perturbation was less than 2% showing the effectiveness of the integral component in eliminating residual steady-state errors. The ±5% testing verifies that IC-IR provides accurate tracking and high-quality power under realistic conditions of irradiance noise and micro-transients, and therefore is suitable for grid-connected applications where irradiance levels change rapidly and intermittently (e.g., clouds passing over, soiling variability, inverter measurement noise, etc.).

Figure 10 depicts how both Photovoltaic (PV) systems respond to a ±5% irradiance fluctuation through their voltage responses. A ±5% variation in irradiance will cause the Maximum Power Point Tracking (MPPT) operating Voltage (VMPP) to be slightly displaced from its nominal value, indicating that the controller provides excellent voltage regulation. The amount of displacement for the monocrystalline PV system is about ±2V (i.e., ≈ 0.9% of nominal voltage), while for the polycrystalline PV system it is about ±3V (i.e., ≈ 1.6%).

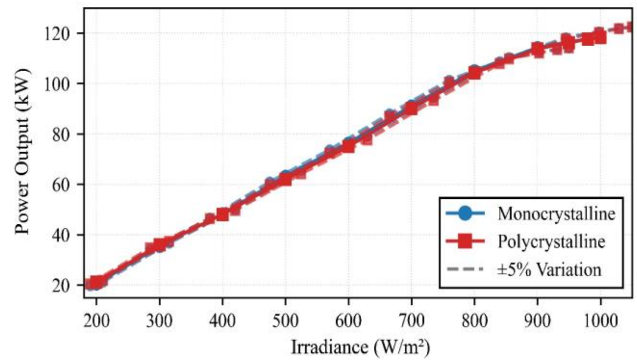

Fig. 9 Impact of ±5% irradiance variation on power output using IC-IR MPPT controller for monocrystalline and polycrystalline PV systems

Both of these minor displacements are due to the rapid corrective actions taken by the incremental-conductance with integral regulator (IC-IR) control algorithm when irradiance varies. The integral term rapidly corrects any incremental conductance error that occurs as a result of each irradiance fluctuation and restores the duty cycle nearly instantaneously, eliminating both the possibility of oscillatory drift and prolonged settling time of the duty cycle.

Therefore, a steady-state voltage error of less than 2% and no overshoot during rapid irradiance recovery indicate that the dc-link voltage stability and the overall MPPT loop are maintained.

The data in Figure 10 demonstrates the dynamic performance and validates the previous power data shown in Figure 9, thereby demonstrating the ability of the IC-IR MPPT controller to maintain both power and voltage stability at short-term irradiance fluctuations - which is an essential benefit over other classical incremental-conductance or perturb-and-observe techniques that generally produce 4–6 V of voltage oscillation in similar testing conditions [3, 10, 15].

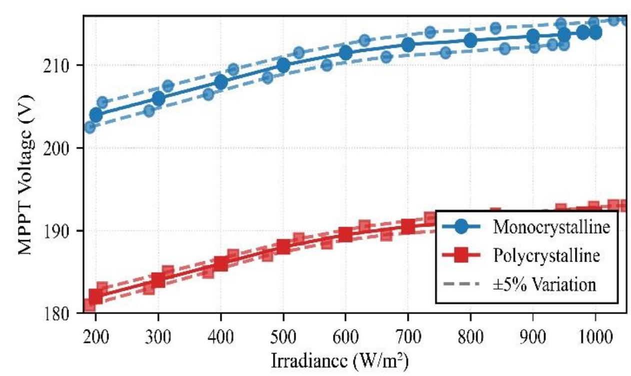

Fig. 10 MPPT voltage shift under ±5% irradiance variation

Figure 11 presents a comparative economic assessment of the proposed IC-IR MPPT controller, including the costs of the IC-IR controller, additional annual energy yield, and financial savings compared to the conventional IC technique for a 120 kW grid-connected PV system. The IC-IR technique has achieved an additional 3.46 MWh yr−1 of useful energy by improving tracking accuracy and reducing dynamic losses. Given the current Kyrenia electricity tariff price of 0.25 USD kWh-1, this represents an annual saving of approximately 865 USD. The added cost to implement the IC-IR controller – estimated at approximately 600 USD for both the digital control and sensing circuits – can be recuperated in approximately 0.7 years of operation.

At the end of a 20-year operational life, the cumulative additional energy produced will exceed 69 MWh, resulting in a total net economic gain of more than 17,000 USD. As such, the resultant Cost-Benefit Ratio (CBR) is approximately 5.3:1, indicating that each dollar invested in the IC-IR upgrade will provide more than five dollars in total benefits over its life.

As such, these findings indicate that the IC-IR controller not only achieves superior technical performance, as evidenced by Figures (7)-(10) but also offers significant economic advantages, providing a cost-effective and sustainable MPPT solution for large-scale grid-tied PV systems in the Kyrenia region [3, 10, 16].

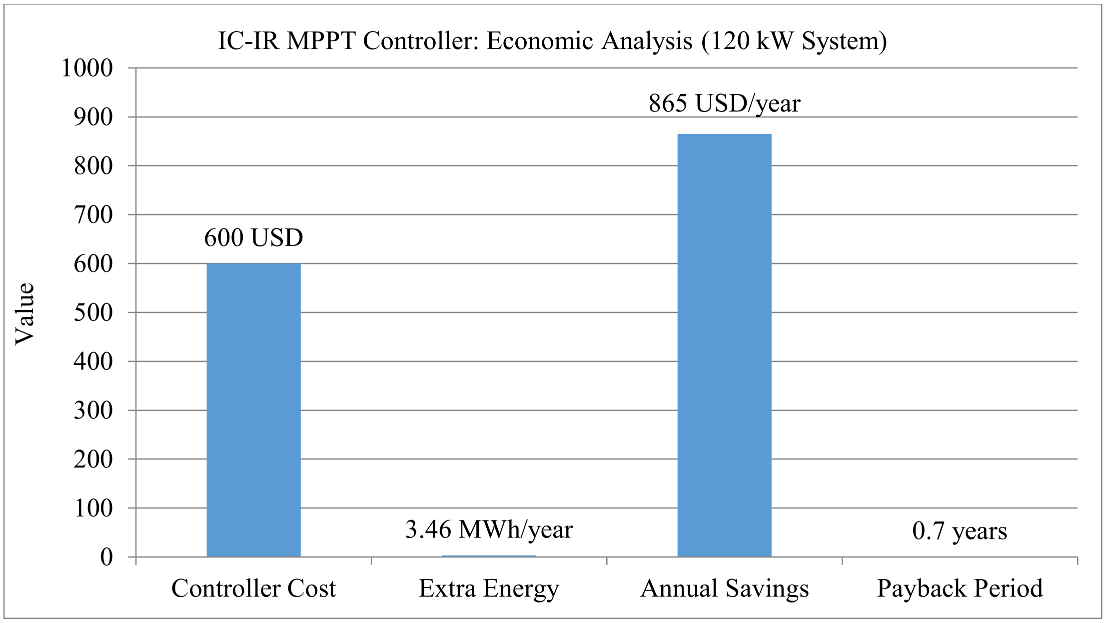

Fig. 11 Cost-benefit analysis of IC-IR MPPT

5. Conclusion

A comparative study of monocrystalline and polycrystalline Photovoltaic (PV) module operation using an Incremental-Conductance + Integral-Regulator (IC-IR) Maximum Power Point Tracking (MPPT) controller was conducted on a 120 kW grid-connected PV array. An effective combination of the fast dynamic tracking capability of the Incremental Conductance (IC) method and an integral compensation term to eliminate steady state error was achieved through the development of the IC-IR control scheme. Simulated data show that the IC-IR technique exhibits better tracking precision and dynamic stability than does conventional IC MPPT control. For monocrystalline PV arrays, the MPPT tracking efficiency ranged from 96.7 to 99.1%, while for polycrystalline arrays, it ranged from 97.0 to 98.9%. Grid side power loss remained < 2.5% under full solar irradiance. A reduction of ≈ 37% in the amplitude of voltage oscillation and a steady-state error of < 2% was achieved during rapid ± 5% irradiance perturbations. The MPPT voltage deviation was limited to ±2 V for monocrystalline and ±3 V for polycrystalline modules, confirming good voltage regulation. While technical performance was demonstrated, the economic evaluation shows that the proposed design is cost-effective. Approximately $600 in hardware costs are added to the IC-IR controller; however, it produces approximately 3.46 MWh of additional energy per year, generating approximately $865 in annual savings, with a payback period of 0.7 years and a cost/benefit ratio of ~ 5.3: 1 at the current Kyrenia tariff rate of 0.25 USD/kWh. Therefore, these findings demonstrate that the IC-IR MPPT not only increases technical efficiency but also generates economic benefits over the system's lifetime. In conclusion, the IC-IR controller presents a robust, accurate, and cost-effective MPPT strategy for grid-tied PV systems. Future work will focus on implementing the controller's hardware, validating its performance in real time under varying weather conditions and partial shading, and expanding the algorithm to include hybrid PV-wind and Micro-grid configurations for complete renewable energy systems.

References

[1] Ciprian Cristea, Maria Cristea, and Radu-Adrian Tîrnovan, "Techno-Economic Assessment of Grid-Connected Residential Rooftop Photovoltaic Systems using Various Photovoltaic Technologies: A Case Study in the Northwestern Romania," *2021 International Conference on Electromechanical and Energy Systems (SIELMEN)*, Iasi, Romania, pp. 408-412, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Neha Kumari et al., "Performance Investigation of Monocrystalline and Polycrystalline PV Modules under Real Conditions," *IEEE Access*, vol. 12, pp. 169869-169878, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Karri V.V. Satyanarayana, and H.Z. Amrolia, "Energy Management of Grid Connected PV System without Energy Storage using High Gain Converter for DC Microgrid Applications," *2025 IEEE 1st International Conference on Smart and Sustainable Developments in Electrical Engineering (SSDEE)*, Dhanbad, India, pp. 1-6, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] William Phipps, and Divya Sivadas, "Economic Evaluation of a Grid-Connected PV System at Otago Polytechnic," *2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Coimbatore, India, pp. 1-6, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[5] Al Imran Fahim, and Salah Uddin Yusuf, "Energy Management System of a PV-Based Grid-Connected Electric Vehicle in Bangladesh," *2023 10th IEEE International Conference on Power Systems (ICPS)*, Cox's Bazar, Bangladesh, pp. 1-6, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[6] Maha M. Hassan et al., "An improved Perturb and Observe based MPPT Method and Power Stabilization for Grid Connected PV System," *2021 22nd International Middle East Power Systems Conference (MEPCON)*, Assiut, Egypt, pp. 483-490, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Ong-art Sadmai, Boonyang Plangklang, and Somchai Hiranvarodom, "Performance Analysis of a 3kWp Grid Connected PV System in the University of Pathumthani Province," *2021 9th International Electrical Engineering Congress (iEECON)*, Pattaya, Thailand, pp. 73-76, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Rituraj Rituraj, and Péter Kádár, "Performance Analysis of 50 KWp Rooftop Grid-Connected PV System," *2021 IEEE 19th International Symposium on Intelligent Systems and Informatics (SISY)*, Subotica, Serbia, pp. 177-182, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] Nablous El Hajjam et al., "Comparative Study of Production of Three Grid-Connected PV Systems in Two Cities of Morocco," *2021 9th International Renewable and Sustainable Energy Conference (IRSEC)*, Morocco, pp. 1-4, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[10] Saibal Manna, and Ashok Kumar Akella, "Comparative Analysis of Various P&O MPPT Algorithm for PV System Under Varying Radiation Condition," *2021 1st International Conference on Power Electronics and Energy (ICPEE)*, Bhubaneswar, India, pp. 1-6, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] P.K. Vineeth Kumar, and K. Manjunath, "A Comparitive Analysis of MPPT Algorithms for Solar Photovoltaic Systems to Improve the Tracking Accuracy," *2018 International Conference on Control, Power, Communication and Computing Technologies (ICCPCCT)*, Kannur, India, pp. 540-547, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[12] Mohamed Ahliouati, Rabie El Otmani, and Khalid Kandoussi, "Performance Analysis of Monocrystalline PV Module Under the Effect of Moroccan Arid Climatic Conditions," *2023 3rd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)*, Mohammedia, Morocco, pp. 1-6, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Syed Ayan et al., "Soiling-Induced Efficiency Losses in Photovoltaic Systems: A Comparative Study of Monocrystalline Monofacial and Bifacial Panels," *2025 International Conference on Power Electronics Converters for Transportation and Energy Applications (PECTEA)*, Jatni, India, pp. 1-6, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[14] Aryulius Jasuan, Zainuddin Nawawi, and Hazairin Samaulah, "Comparative Analysis of Applications Off-Grid PV System and On-Grid PV System for Households in Indonesia," *2018 International Conference on Electrical Engineering and Computer Science (ICECOS)*, Pangkal, Indonesia, pp. 253-258, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[15] Thanh-Dong Ngo, Cao-Tri Nguyen, and Sy Ngo, "Enhanced MPPT-Based Control Strategy for Single-Phase Grid-Connected Inverters in PV Systems," *2025 10th International Conference on Applying New Technology in Green Buildings (ATiGB)*, Danang, Vietnam, pp. 483-488, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[16] Rukhsana Choudhury, and Galib Hashmi, "Development of a Dual-Operation Grid-Connected Rooftop PV System with Capacity and Space Optimization Under NEM Guidelines in Bangladesh," *2024 IEEE International Women in Engineering (WIE) Conference on Electrical and Computer Engineering (WIECON-ECE)*, Chennai, India, pp. 222-227, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Raed Alcharea, and Waseem Saeed, "Evaluating Grid Connected Photovoltaic System Performance and Estimating the Produced Electric Power," *2021 12th International Renewable Engineering Conference (IREC)*, Amman, Jordan, pp. 1-4, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ankur Paras, Upendra Prasad, and Amit Kumar Choudhary, "Comparative Assessment of ANN-based MPPT Algorithm for Solar PV System," *2022 IEEE North Karnataka Subsection Flagship International Conference (NKCon)*, pp. 1-6, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ahmed Saidi, and Chellali Benachaiba, "Comparison of IC and P&O Algorithms in MPPT for Grid Connected PV Module," *2016 8th International Conference on Modelling, Identification and Control (ICMIC)*, Algiers, Algeria, pp. 213-218, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[20] Azmi Saleh et al., "Comparison of MPPT Fuzzy Logic Controller based on Perturb and Observe (P&O) and Incremental Conductance (InC) Algorithm on Buck-Boost Converter," *2018 2nd International Conference on Electrical Engineering and Informatics (ICon EEI)*, Batam, Indonesia, pp. 154-158, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[21] Göksel Gökkuş, and Mustafa Sacid Endiz, "Simplified P&O MPPT Algorithm for Accurate Power Tracking in Photovoltaic Systems," *2025 International Conference on Computer Technology Applications (ICCTA)*, Vienna, Austria, pp. 217-221, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[22] K.H. Akhil et al., "Comparison of Performance of MPPT Algorithms for Solar Powered Battery Charging Applications," *2024 3rd International Conference for Advancement in Technology (ICONAT)*, GOA, India, pp. 1-5, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[23] Mohammad R. Al-Soeidat, Alexis Cembrano, and Dylan D.C. Lu, "Comparing Effectiveness of Hybrid MPPT Algorithms Under Partial Shading Conditions," *2016 IEEE International Conference on Power System Technology (POWERCON)*, Wollongong, NSW, Australia, pp. 1-6, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[24] Christopher C. Bondoc et al., "Holistic Assessment of Monocrystalline Silicon (mono-Si) Solar Panels with Recycled Content vs. Virgin-Grade Materials," *2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)*, San Juan, PR, USA, pp. 1-3, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Nur Adibah Jumien et al., "Performance of a 2.8 Kwp Monocrystalline Free-Standing Grid-Connected Photovoltaic System at SIRIM Berhad," *2015 IEEE 6th Control and System Graduate Research Colloquium (ICSGRC)*, Shah Alam, Malaysia, pp. 93-97, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[26] Jian Zhang et al., "Coordinated Control Strategy of Grid-Connected Photovoltaic Generation System," *2023 8th Asia Conference on Power and Electrical Engineering (ACPEE)*, Tianjin, China, pp. 579-584, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[27] Suresh Singh, Rakesh Kumar, and Vivek Vijay, "Performance Analysis of 58 kW Grid-Connected Roof-Top Solar PV System," *2014 6th IEEE Power India International Conference (PIICON)*, Delhi, India, pp. 1-6, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[28] Nasser Aldahmashi, Yasin Khan, and Abdulrahman Alamoud, "Techno-Economic Analysis of Grid-Connected Rooftop Solar PV Systems in Saudi Arabia," *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, Fort Lauderdale, FL, USA, pp. 2217-2221, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[29] Zhipeng Fan et al., "Perturb and Observe MPPT Algorithm of Photovoltaic System: A Review," *2021 33rd Chinese Control and Decision Conference (CCDC)*, Kunming, China, pp. 1413-1418, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[30] Paramjeet Singh Paliyal et al., "Optimization of Solar Photovoltaic Array In-Depth Analysis of Perturb and Observe MPPT Algorithm," *2024 International Conference on Advances in Computing, Communication and Materials (ICACCM)*, Dehradun, India, pp. 1-6, 2024. [CrossRef] [Google Scholar] [Publisher Link]