

Design and Experimental Evaluation of a Bifacial Solar Photovoltaic–Based Electric Vehicle Charging System with Rear-Side Reflection Enhancement

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Research Article

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Design and Experimental Evaluation of a Bifacial Solar Photovoltaic–Based Electric Vehicle Charging System with Rear-Side Reflection Enhancement

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Abstract— In order to reduce the reliance on the grid and minimize the amount of carbon emissions produced through transportation, the rapid adoption of electric cars (EVs) has enhanced the demand for green and sustainable charging infrastructure. Solar-powered EV charging systems provide an efficient solution; however, the inherent limitation of traditional monofacial photovoltaic (PV) technology is that it depends on harnessing solar irradiance from the front side. Bifacial photovoltaic technology helps overcome this limitation by harnessing energy from the front and back sides of the panel. This results in an enhanced output for the surface in comparison to traditional photovoltaic technology. The reflectivity of the surface and the technology can have an enormous impact on the back side. This paper, apart from statistically investigating the impact of different reflexive surfaces on energy generation and EV charging efficiencies, proposes an efficient design for a bifacial photovoltaic technology-based EV charging system. The high-power 545 W bifacial PV module, coupled with the EV battery charging device and a maximum power point tracking charge controller, is adopted to form a comparative experiment configuration. Given the same outside working environment, three efficient rear-side reflected materials, such as white paint, silver paint, and aluminum foil, are experimented upon. Voltage, current, power output, irradiance, temperature, etc., are the important electric and environmental parameters that are continuously monitored to measure the rear-side efficiency and the overall efficiency of the system. According to experimental findings, the efficiency of a bifacial PV system is significantly enhanced through rear-side optimization. Aluminum foil gains the highest amount of irradiance and achieves a power gain of 15-25 %. Additionally, the modified system showed increased stability in charging current as well as a reduced charging time under conditions of varying irradiance levels, particularly for EV battery charging. From the result, it is evident that MPPT control in conjunction with low-cost rear-side reflective optimization is a cost-effective, scalable, and sustainable strategy for solar-powered EV charging.

Keywords: Bifacial photovoltaic (PV), Electric vehicle (EV) charging, Solar-powered EV charging, Rear-side reflective surfaces, Aluminium foil reflector, MPPT charge controller, Renewable energy, Power enhancement, Sustainable transportation.

1. INTRODUCTION

The growing need to shift from a polluting, fossil fuel-based energy supply to clean and sustainable energy has led to the widespread deployment of solar PV (SPV) systems around the world. Bifacial photovoltaic (PV) modules are one of the emerging PV technologies which gained significant attention due to their ability to harness solar energy from both the front and back sides of the module, generating more power than standard monofacial PV modules [1]. With the recent advances of bifacial PV technology, the PV system has become even more suitable for application in building-integrated PV system, utility-scale PV system and distributed PV system [2]. The basic principle of capturing reflected radiation on the back of a bifacial module was first proven in small-scale experimental testworks where significant amounts of additional power were generated from albedo-collecting configurations were reported [3].

Several environmental and geometrical factors such as the orientation and tilt angle of module, row-to-row spacing, ground reflectivity, and operating conditions have significant effect on the energy yield of a bifacial PV system [4]. One such factor is the ground albedo, which directly affects the amount of radiation available for the back side of the bifacial module as a higher reflectivity surface means increased radiation. Owing to this, the design and layout of bifacial PV farms need to be carefully designed to capture as much light as possible on the rear surface while minimizing the shading and optical losses [5]. Experimental and theoretical study has shown that the electrical performance and the overall energy yield of bifacial modules can significantly be affected by the module arrangement in space [6].

There are also great potential for agrivoltaic applications, where PV power generation and agricultural work take place on the same land. Optimal system set-up gives better land-use efficiency and still allows for good crop production conditions [7]. These systems are not only affected by the geometry of the modules but also by the interaction of the PV modules and surrounding ground and vegetation. Therefore, it is crucial to accurately characterize the reflectance characteristics of the environment to accurately predict the irradiance of the rear side and optimise the bifacial PV output [8].

However, bifacial PV modules have also been gaining traction for building and other infrastructure applications due to the potential to tap into reflected and diffuse radiation from surrounding surfaces. If appropriate architectural surfaces are

available, a building-integrated bifacial configuration may generate further electricity and be used effectively [9]. Vertical bifacial PV installations are especially appealing for façade and infrastructure use owing to their geometry that can be designed to collect energy at various times of the day and can provide useful performances under appropriate irradiation conditions [10].

The geometry of the module and ground albedo are among the other factors influencing the amount and quality of radiation that reaches the back of the bifacial module. Therefore, an artificial reflector design may offer a feasible solution to increase the rear side irradiance, and hence the bifacial PV energy yield. Experimental comparisons of bifacial to monofacial PV system under various ground-albedo conditions also have revealed that the electrical advantage of the bifacial modules is heavily dependent on the reflectivity of the surrounding environment [12]. Moreover, optical and thermal operating conditions of a PV installation can affect the real energy gain, hence the importance of taking into account both optical and thermal operating conditions [13].

Optical response of a Bifacial PV module is not only dependent on the magnitude of surface reflectivity. Additionally, the energy spectrum of the reflected radiation can affect the PV conversion as the PV cells respond differently to different wavelengths. The electrical performance of PVs has been shown to be affected by the spectral properties of the incident and reflected radiation in studies of the spectral albedo [14]. For bifacial systems, this is especially true since the rear-side irradiance can be from a surface with very different spectral properties. The effect of spectral albedo has thus been studied, both theoretically and experimentally, on the performance of bifacial solar cells [15].

It is therefore crucial to accurately model the surrounding optical environment for reliable bifacial PV performance prediction. To estimate more realistically the irradiance available to PV systems, advanced albedo models have been developed that take into consideration the geometric and spectral properties of reflecting surfaces [16]. These methods can be especially helpful in situations where the back side irradiance is impacted by non-uniform surfaces, vegetation, artificial reflectors, or complex installation geometries.

More recently, more sophisticated PV technologies (bi-facial PV) and configurations (using reflectors) have been studied and investigated to improve the energy yields even more. For example, bifacial tandem photovoltaic modules are an example of how bifacial light collection with advanced photovoltaic device architectures can be achieved [17]. However, recent systematic comparisons of various ground-reflector configurations indicate that the optical properties and geometry of the reflectors play an important role in the rear-side irradiance and bifacial energy gain [18]. Infrastructure-integrated systems with reflective structures have also shown the ability of purposefully designed surrounding surfaces to enhance the optical environment of bifacial PV modules [19].

Natural surfaces can be more complex due to the fact that they have a reflectance that is, in general, direction dependent and non-uniform. Angular and spectral reflection properties of vegetation, soil, crop surface and other environmental materials can vary. Thus, the bifacial PV system's surface characteristics, geometry of PV modules, and the direction of both the incident and reflected radiation are important factors to take into account when assessing PV systems realistically in natural environments.

Therefore, the design parameters of PV systems and the optical conditions on the rear need to be understood in detail to achieve performance improvements for bifacial PV systems. Rear side irradiance can be boosted by use of engineered reflective surfaces without in principle changing the bifacial module itself. Therefore the impact of the rear-side reflective surfaces on the bifacial PV performance is the focus of the present study, and the possibility of improving electrical energy production by controlled irradiation of the rear side is studied. The key parameters that impact the bifacial PV performance – reflectivity, reflector configuration, rear-side irradiance and electrical output – were taken into account and formed a good basis for maximizing the energy yield of bifacial PV systems.

2. REAR-SIDE PERFORMANCE ENHANCEMENT

An emerging research area is the bifacial photovoltaic (PV) system, which can utilize solar radiation that falls on either side of the PV module. Bifacial modules are able to capture reflected, scattered and diffuse radiation from the surrounding environment to generate electrical energy, whereas traditional monofacial modules only capture radiation from the front. Studies of bifacial PV technology have shown that PV systems have several operational benefits, technical advances, and become more relevant to today's PV systems [1]. Recent advances in bifacial module technology and integration into buildings have proven the feasibility of bifacial PV systems for a variety of distributed and infrastructure applications [2]. Early research efforts showed that electrical production of bifacial solar cells could be significantly increased under the right albedo conditions [3] and the fundamental idea of using rear side reflected radiation was validated.

This has led to installation and system-design parameters to be considered as key research areas for enhancing the bifacial energy yield. The mounting height of the modules, PV module tilt angle, PV module orientation, row spacing, and environmental conditions around the modules would affect the performance of the bifacial PV system [4]. Studies of bifacial PV configurations have shown that rear-side PV module exposures can be enhanced by proper module geometry which can

result in higher annual energy yields for PV plants [5]. Different bifacial solar farm configurations and array arrangements have also been analysed experimentally and theoretically, which has further confirmed the importance of system geometry and array arrangement on the overall bifacial gain [6].

Another field of agrivoltaic application that has garnered great interest is bifacial PV technology, in which the PV generation and agronomic production take place in the same space. These arrangements can increase the efficiency of land use, while still providing ideal conditions for agricultural production [7]. Among these systems, the effect of module geometry, ground conditions and the surrounding optical environment on the rear-side irradiance that results from the interaction of the three must be taken into account, since the rear irradiance is a function of the surrounding optical environment [8]. Bifacial modules have also been shown to capture reflected radiation from adjacent surfaces and enhance energy generation compared to conventional monofacial modules, when integrated within buildings and other structures [9]. Vertical bifacial devices have also been explored for façade integration, with the surrounding due to the orientation and surrounding surfaces affecting the temporal profile of solar energy generation [10].

The reflective surface is another significant technique for enhancing the rear side irradiance. Artificial reflector configurations can be developed to direct more solar radiation toward the back of the bifacial modules to increase the electric power that can be generated [11]. The experimental results have demonstrated that the energy gain offered by the bifacial approach is much larger than that of the conventional low-albedo environment for different surface albedo conditions [12]. Besides optical conditions, the module temperature can also affect the energy gain of bifacial installations, as thermal issues must also be taken into account when assessing the performance of a bifacial system [13].

Reflectance of a reflecting surface is not the only factor to judge its effectiveness. Another spectral impact on the PV conversion is the wavelength-dependent spectral response of the solar cells themselves. The significance of the spectral characteristics of reflecting surfaces for the assessment of PV performance has then been proven by investigating spectral albedo [14]. Theoretical and experimental research has also shown that the spectral composition of the rear side irradiance can affect the energy gain of a bifacial solar cell [15]. Therefore, it is important to have models that can simulate both the quantity and spectrum of reflected radiation when predicting bifacial PV performance. In response to this, advanced albedo models have been developed to include the geometric and spectral properties of reflecting surfaces and to enhance the accuracy of the estimation of the irradiance for solar-energy applications [16].

In recent times, bifacial technology has begun to be applied to more complex PV architectures and designed optical environments. The potential of combining higher level cell structures with rear side energy collection has been proven by bifacial perovskite/silicon tandem photovoltaic modules [17]. Meanwhile, reflective properties, geometry, and installation conditions have been found to have a significant impact on the rear-side irradiance and consequent bifacial energy gain through systematic studies of ground reflectors [18]. Another aspect of reflective infrastructure that has been studied is to control the spatial and angular distribution of radiation that is incident upon bifacial PV systems [19].

To obtain more detailed knowledge of rear-side irradiance, the optical interaction between radiation and natural surfaces needs to be taken into account. Microfacet based optical models have been used to understand the geometric behavior of reflecting and refracting surfaces where the surface interactions are not ideal [20]. Leaves and crop canopies also have wavelength-dependent reflection and transmission properties, adding to the complexity of vegetation. Leaf geometry and canopy geometry studies have thus been utilized to study the interaction between solar radiation and vegetation [21]. Reflectance and transmittance of each leaf is important for radiation propagation through agricultural environment [22]. There have also been developments in estimating biochemical and spectral properties that affect vegetation reflectance by using advanced leaf optical models [23].

This angular distribution of reflected radiation from the vegetation is also relevant for estimating the reflected irradiance on the back of bifacial PV modules. Research on realistic vegetation rendering and canopy representation has taken place and shown the significance of leaf geometry and directionality of illumination in defining the optics of grass and crop surface [24]. Experimental studies of the bidirectional reflectance properties of vegetation have also been conducted, which have added information about the dependence of the surface reflectance on the illumination and observation angles [25]. Multi-angular studies of natural vegetation have also shown that the reflectance of an individual plant and canopies can change significantly as a function of viewing geometry [26]. Another effect, the hotspot effect, where the direction of illumination and observation come close, is also of great importance for vegetation reflectance [27].

Later, more sophisticated models of canopy-reflectance were built to model directional characteristics of vegetation surfaces and to better simulate the angular scattering phenomenon [28]. Optical properties are especially important for PV systems that are installed above or near vegetation, as the back-side irradiance can change depending on the solar elevation, geometry of the PV module, and canopy structure. It has been recently found that the bi-facial PV yield calculations need to include the directional vegetation properties because of the work on spectro-angular grass reflectance [29]. Bidirectional reflectance representation can be used to describe how reflected radiation changes as a function of illumination and viewing direction, and thus mathematically describe complex environmental surfaces [30].

Reliable databases of spectra have also contributed to the characterization of natural and artificial reflecting surfaces. Spectral libraries that contain a broad collection of experimental data on reflectance of different environmental materials can, thus, be useful for more realistic optical simulations of PV systems [31]. More sophisticated representations of vegetation under dynamic illumination have also shown that the surface geometry of the vegetation and its directionality of illumination are critical to the accurate representation of environmental reflectance [32]. Additionally, agricultural surface optical properties can change due to differences in rainfall, biomass, and vegetation density and the different environmental conditions throughout the year, which can affect the radiation received by any adjacent bifacial PV systems [33].

In recent years, engineered reflector systems and dynamic environmental conditions are increasingly emerging as the focus of research to achieve further improvement in bifacial PV energy yield. Reflector-assisted configurations have shown to be able to improve bifacial performance in specific seasons and solar angles [34]. For agrivoltaic applications, it is shown that the consideration of the simultaneously variable spectrum, the ground reflectance and the crop characteristics is important to accurately calculate photovoltaic current and energy production [35].

While significant advances have been made in the understanding of bifacial PV systems, there are still hurdles in accurately modelling PV performance for application-specific geometry, environmental variability, the characteristics of the reflector and spectral-angular reflectance. Specifically, the practical outdoor bifacial module and engineered rear-side reflectors need to be further experimentally investigated. Thus, further research is needed to establish a comprehensive strategy including optical enhancement of the rear side, characterization of the albedo, optimization of reflectors, and assessment of electrical performance to enable reliable and greater energy yield from future bifacial PV installations.

3 . System Architecture and Working Principle

3.1 Overall System Architecture

The proposed system architecture focuses on optimizing the reflectivity on the back surface of the PV module for bifacial modules, in order to make efficient and green charging of EVs easier. It comprises of four major subsystems: a bifacial solar PV generation unit, a rear side reflective surface arrangement, a power conditioning and control unit and an EV battery charging unit. The integration of these subsystems allows for safe and reliable battery charging, and optimal utilization of solar energy.

A high power 545 W bifacial photovoltaic module is the main energy source. Unlike the conventional monofacial module, the bifacial module will collect sunlight on the front surface (direct and diffuse solar radiation) as well as on the back surface (reflected solar radiation). The designed space in the back of the panel is achieved by positioning the reflective materials at the bottom of the panel. The maximum power point tracking (MPPT) controller, which has the ability to change the operating voltage and current, is connected to the electrical output of the photo-voltaic module.

Considering the modular architecture design of the whole system, it can be customized according to the difference of EV battery capacity and charging power, and the difference of application scenes, for example, standalone off-grid charging station.

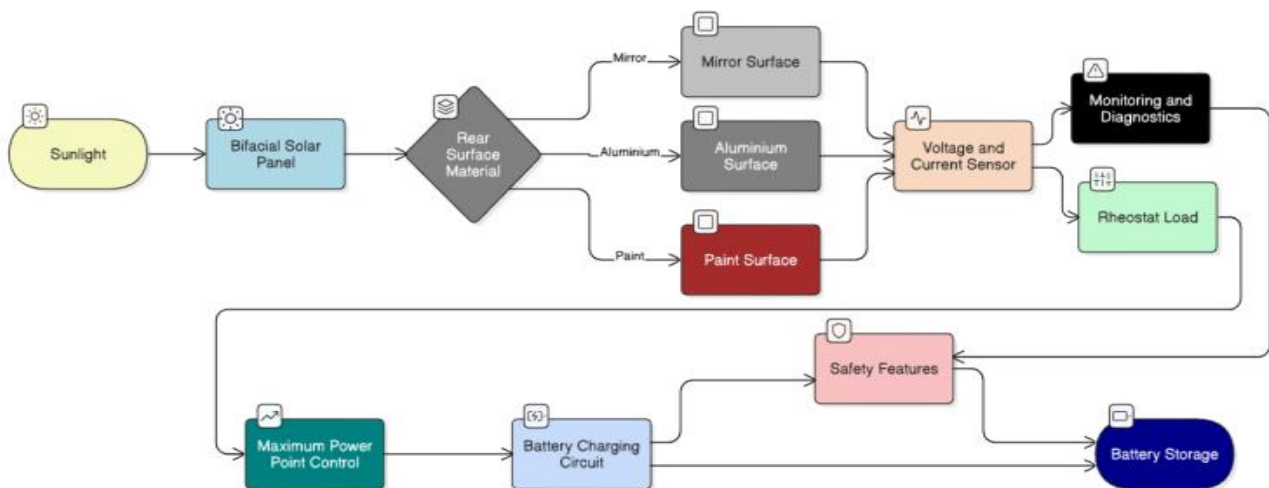


Fig 1 . Overall architecture of the proposed bifacial PV-based EV charging system with rear-side reflective enhancement.

3.2 Rear-Side Reflective Surface Integration

The optical properties of the surface present under the panel greatly influence bifacial PV surface performance. The bifacial PV module is then aligned with the proposed structure and a specific angle and elevation are chosen for an unobstructed exposure of the back surface to the irradiance reflected. Aluminium foil, silver paint and white paint are applied as useful materials to the rear surface of the PV to determine the impact of harvesting energy.

On the other hand, surfaces such as those painted white exhibit enhancement on a range of angles for the sun, mainly through diffuse reflection. Silver has medium diffuse and specular reflectivity. The specular reflectance component of aluminium foil is high, which means that there is more solar radiation hitting the back surface of the PV module. The system architecture enables this study on virtual methods for improved BSI.

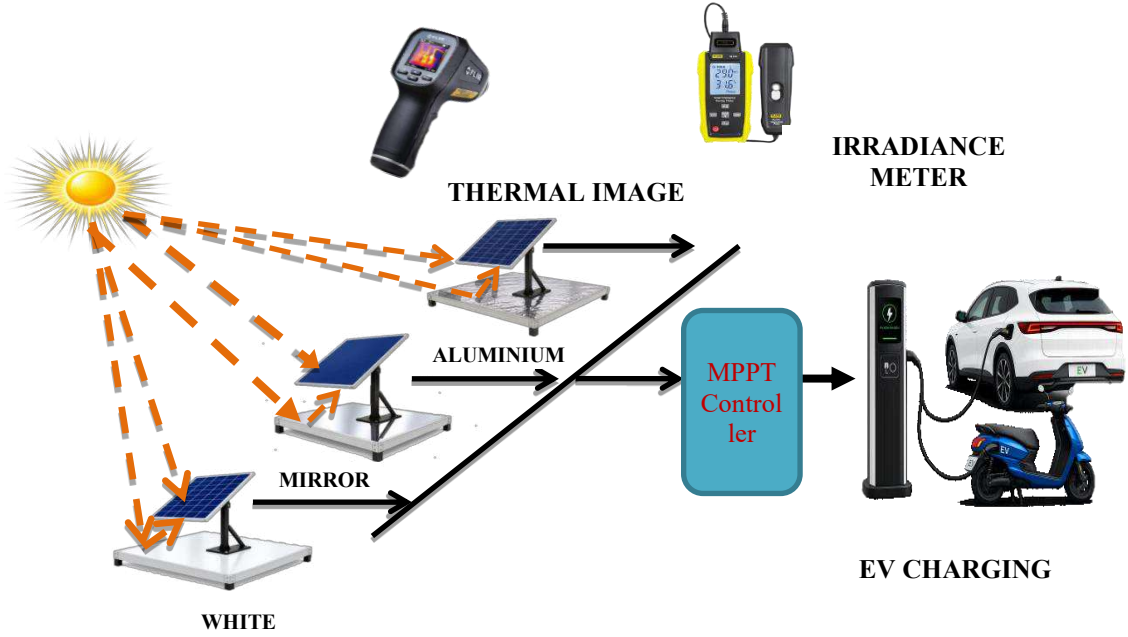


Fig 2 Integration of rear-side reflective materials beneath the bifacial PV module in the proposed EV charging setup.

3.3. Influence of Rear-Side Reflection on the Performance of Bifacial Solar Panels

Unlike monofacial solar PV modules, bifacial solar PV modules can generate more power due to its ability to harness energy from both sides of the modul. The amount of light that gets into the back side of the module plays a significant role in the functionality of the bifacial PV systems. Rear side reflection is when the sun reflects off the ground or from any reflective surface that's below the panel. The reflected rays will increase the overall energy production by increasing the energy on the backside of the module. Despite the moderate diffuse reflectance of white painted surfaces, the highly reflective surfaces such as mirrors and aluminium sheet will be able to reflect more of the solar radiation to the back surface. This is an additional power output of a bifacial module due to excess irradiance. This way, the PV system's back side can be optimised to enhance the overall system performance and energy production of the system by approximately 5 to 25 per cent.

3.4. Mathematical Modelling of Bifacial Irradiance

3.4.1. Front-Side Irradiance on the PV Module

The total irradiance incident on the front side of the panel is

$$G_{front} = G_b + G_d + G_r \quad (1)$$

Where

G_{front} = total irradiance on front surface(W/m²)

G_b = beam/direct irradiance
 G_d = diffuse irradiance
 G_r = ground reflected irradiance

3.4.2. Ground Reflected Irradiance (Albedo Component)

The reflected irradiance from the ground surface is

$$G_r = \rho_g \times GHI \quad (2)$$

Where

ρ_g = ground reflectance (albedo coefficient)
 GHI = global horizontal irradiance

Table I. Ground Surface Reflectance (Albedo) Values for Different Reflective Materials.

Surface	Reflectance (ρ_g)
Soil	0.15–0.25
White paint	0.70–0.85
Aluminium sheet	0.60–0.75
Mirror	0.85–0.95

3.4.3. Rear-Side Irradiance of Bifacial Module

The rear irradiance reaching the bifacial panel can be approximated by

$$G_{rear} = \rho_g \times GHI \times F_{view} \quad (3)$$

Where

G_{rear} = irradiance on rear surface (W/m²)
 ρ_g = reflectivity of mirror/white/aluminum surface
 F_{view} = view factor between ground reflector and PV rear surface

3.4.4. View Factor for Tilted PV Module

$$F_{view} = (1 - \cos\beta)/2 \quad (4)$$

Where

β = tilt angle of the PV module

3.4.5. Total Irradiance on Bifacial Module

$$G_{Total} = G_{front} + \phi \times G_{rear} \quad (5)$$

Where

G_{total} = effective irradiance on bifacial module
 ϕ = bifaciality factor (typically 0.65–0.90)

3.4.6. Reflector Surface Irradiance Enhancement

When using a reflector (mirror, white paint, aluminium)

$$G_{rear} = GHI \times \rho_r \times \eta_{geom} \quad (6)$$

Where

ρ_r = reflector reflectivity
 η_{geom} = geometric reflection efficiency

Table II. Reflectivity of Rear-Side Reflective Materials

Reflector	Reflectivity
Mirror	0.9–0.95
White painted surface	0.75–0.85
Aluminum sheet	0.65–0.80

3.4.7. Reflection Loss Analysis of Reflector Surfaces

3.4.7.1. Basic Reflection Loss Formula

Reflection loss is calculated as:

$$L_r = (1 - \rho_r) \times G_{\text{inc}} \quad (7)$$

Where

L_r = reflection loss (W/m²)

ρ_r = reflectivity of reflector surface

G_{inc} = incident irradiance on reflector (W/m²)

3.4.7.2. Reflected Irradiance from Reflector

The irradiance reflected toward the rear side of the PV panel:

$$G_{\text{ref}} = \rho_r \times G_{\text{inc}} \quad (8)$$

Where

G_{ref} = reflected irradiance (W/m²)

ρ_r = reflectivity coefficient

3.4.7.3. Reflection Loss Percentage

$$\text{Loss}(\%) = (1 - \rho_r) \times 100 \quad (9)$$

3.4.7.4. Reflection Loss Considering Geometry Factor

In real systems, not all reflected light reaches the PV module due to geometry.

$$G_{\text{rear}} = \rho_r \times G_{\text{inc}} \times F_{\text{view}} \quad (10)$$

Reflection loss becomes

$$L_r = G_{\text{inc}} - (\rho_r \times G_{\text{inc}} \times F_{\text{view}}) \quad (11)$$

Where

F_{view} = view factor between reflector and PV rear surface

3.4.7.5. Reflection Loss for Different Surfaces

Table III. Reflection Loss of Different Reflective Surfaces.

Surface	Reflectivity (ρ_r)	Reflection Loss
Mirror	0.90–0.95	5–10%
White paint	0.75–0.85	15–25%
Aluminium sheet	0.65–0.80	20–35%

3.4.7.6. Total Optical Loss in Reflector System

$$L_{Total} = L_r + L_s + L_g \quad (12)$$

Where

L_r = reflection loss

L_s = scattering loss

L_g = geometric loss

On bifacial EV charging system, the complete rear irradiance equation including reflection loss can be written as

$$G_{rear} = GHI \times \rho_r \times F_{view} \times (1 - L_r) \quad (13)$$

3.5. Power Conditioning and Control Unit

The electrical power supplied to the PV module is always affected by the temperature, rear-side reflection intensity and solar irradiance. An MPPT-based charge controller has been adopted in the design to ensure optimum harvesting of power under these changing conditions. The algorithm detects the point of maximum power output of the PV module and the duty cycle of the DC-DC converter is adjusted accordingly.

Irrespective of the climate changes, it ensures that the PV module operates in the most optimum way with the least losses possible. The charging device for EV battery takes the DC output from the MPPT controller. For a reliable and secure operation of the DC-DC MPPT controller, the controller's control unit must be protected against over-voltage, over-current or thermal conditions.

3.6. EV Battery Charging Unit and Energy Flow

The charger for an electric vehicle takes into account a condition in which a certain amount of charging current and voltage is controlled based on the condition of the battery. The main purpose of the MPPT is to harvest the highest power from the bifacial PV module when it is used for charging. The charger controller manages the charging power coming from the battery and avoids overcharging effects and heat stress.

This is a short description of how the system works intrinsically: the front and back face of the Bifacial Module reflect the solar irradiance, increasing the reflection. This enhances the solar irradiance, and the MPPT enhances the extraction process. Which is then used to charge the battery of the EV by extracting and regulating the power. The system, therefore, has the advantage of offering a lower accessible charging power and faster charging compared to other solar systems incorporating monofacial technology.

3.7. Monitoring and Performance Evaluation

During operation, other key electrical and environmental parameters, such as PV voltage, current, PV power, irradiance, temperature and others are monitored in order to assess the performance of the solar panel. With this data, efficiencies can be calculated that account for charging and bifacial gain and rear side contribution. The data obtained can also be used to provide feedback on the MPPT, rear-side reflectance, and EV battery charging.

4. EXPERIMENTAL METHODOLOGY

4.1. Experimental Setup



(A)



(B)



(C)



(D)



(E)



(F)

Fig 3. Experimental setup of the bifacial PV-based EV charging system under different reflective surfaces. (A). Aluminum Foil (B). Mirror (C), (D). White Paint (E), (F). Experimental Setup

The effectivity of a bifacial photovoltaic (PV) electric vehicle charging system was experimentally studied under natural weather and environment to optimize the reflective surface area on the back side of the PV

panel. A high efficiency 545 W solar panel was mounted in a fixed stand in a south facing direction at the optimum angle for the solar panel which equals the latitude of the site. The solar panel was mounted in a location that was easily reached from the front and back for easy access to the back side.

There are three effective and economical means of improving the rear side irradiance, namely aluminium foil, silver paint and white paint. For a fair and consistent comparison, each reflective surface of the solar module should be used, and the tests performed in the same conditions.

4.2. Power Conditioning and Charging Configuration

A Maximum Power Point Tracking (MPPT) charge controller was connected with the electrical output of the bifacial solar PV module. The MPPT controller was used to maintain a constant output voltage of the PV array at the maximum power point (MPP) for varying ambient temperatures and different solar irradiance. The DC output from the MPPT controller was used to charge an electric car battery.

To ensure the safe and reliable operation, the charging system had protection features such as over voltage, over current, and heat protection. Using this system, it was able to be determined how reflection could affect the efficiency of the charging of EV batteries.

4.3. Measurement Instruments and Data Acquisition

Calibrated equipment is used to measure all electrical and environmental factors, ensuring that they are measured with accuracy and repeatability. Digital multi-meters are used to measure PV voltage and PV current, which is used to determine the output power. The amount of solar irradiation on the front and back surface of the bifacial module is measured with a lux meter. The ambient temperature and surface temperature of module is measured by using digital thermometers.

Environmental and sun irradiation measurements were taken throughout the day at fixed time intervals to record variations in the environment and irradiation. For each reflecting surface, data for an entire day was collected as well as for each arrangement.

4.4. Experimental Procedure

There were two major stages in the experimental methodology:

Evaluation of the Rear-Side Reflecting Surface: This is because the rear surface of each PV module was used in turn for evaluation. For this purpose, the data needed for the measurement of the voltage, current and the power output as well as the irradiance and the temperature in regard to the feasibility of the voltage, current and power output of the rear reflection and of the power enhancement was collected.

Based upon the results from the first stage, the surface from which maximum power output was generated was chosen for the EV battery charging tests in the second stage. The value of charging voltage and current and charging time were monitored to monitor the stability and efficient operation of EVs in practical operating condition.

4.5. Performance Evaluation Criteria

EV battery charging patterns, EV battery charging power gain from rear-side reflection, and total power output were some of the major signs considered to check the efficacy of the system. By comparing all the data collected in the context, the best material for rear-side reflection was identified, and in general, efficacy was established in respect to the proposed system.

4.6. PV Power Output Equation

$$P = \eta_{PV} \times A \times G_{total} \quad (14)$$

Where

P = PV power output (W)
 η_{PV} = module efficiency
A = panel area (m²)
 G_{total} = effective irradiance

Rear irradiance with mirror reflector:

$$G_{rear.mirror} = 0.9 \times GHI \times F_{view} \quad (15)$$

Rear irradiance with white surface:

$$G_{rear.white} = 0.8 \times GHI \times F_{view} \quad (16)$$

Rear irradiance with aluminium sheet:

$$G_{rear,Al} = 0.7 \times GHI \times F_{view} \quad (17)$$

Table IV. Typical Rear-Side Irradiance Gain for Different Reflective Materials.

Reflector	Rear Irradiance Gain
Mirror	25–35%
White paint	18–25%
Aluminium sheet	15–22%

5. RESULTS AND DISCUSSION

5.1. Effect of Rear-Side Reflective Surfaces on PV Output

Rear-side reflection enhances the quantity of solar radiation which reaches the back surface of a bifacial photovoltaic module. Examples of reflective materials include mirrors, aluminium sheets, and surfaces painted in white, which reflect the incidence sunlight onto the back of the panel. It is the additional reflected radiation of this extra irradiance to the module that enhances power output and system efficiency.

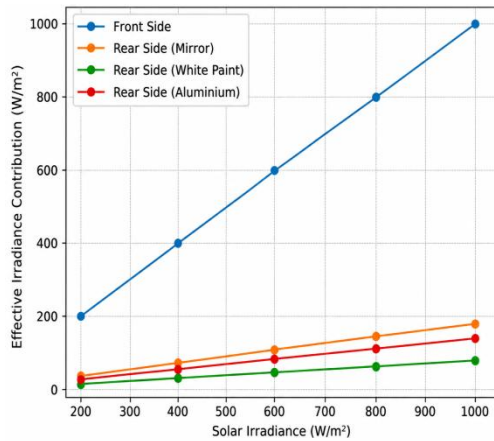


Fig 4. Variation of solar irradiance measured on the front and rear surfaces of the bifacial photovoltaic module under different reflective surfaces

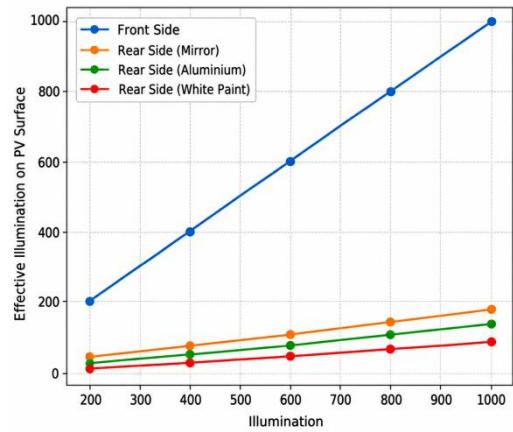


Fig 5. Comparison of illumination levels measured on the front and rear surfaces of the bifacial photovoltaic module for different reflective materials.

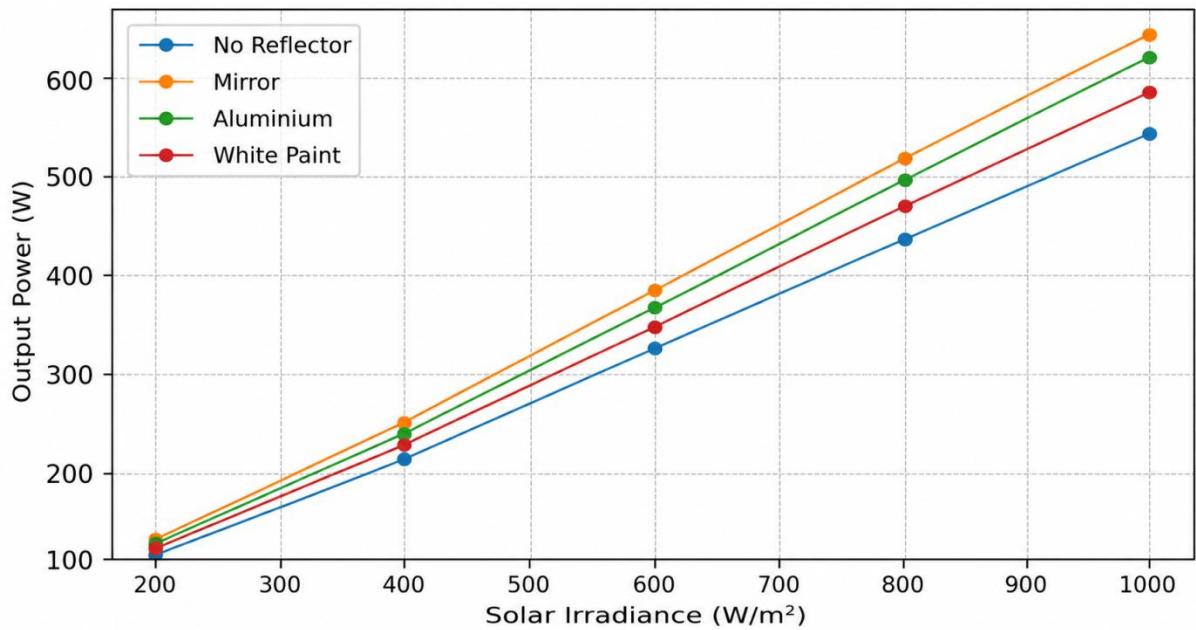


Fig 6. Variations of solar irradiance measured and the output power of the bifacial photovoltaic module under different reflective surfaces.

5.2. Effect of Rear-Side Reflective Surfaces on PV Output

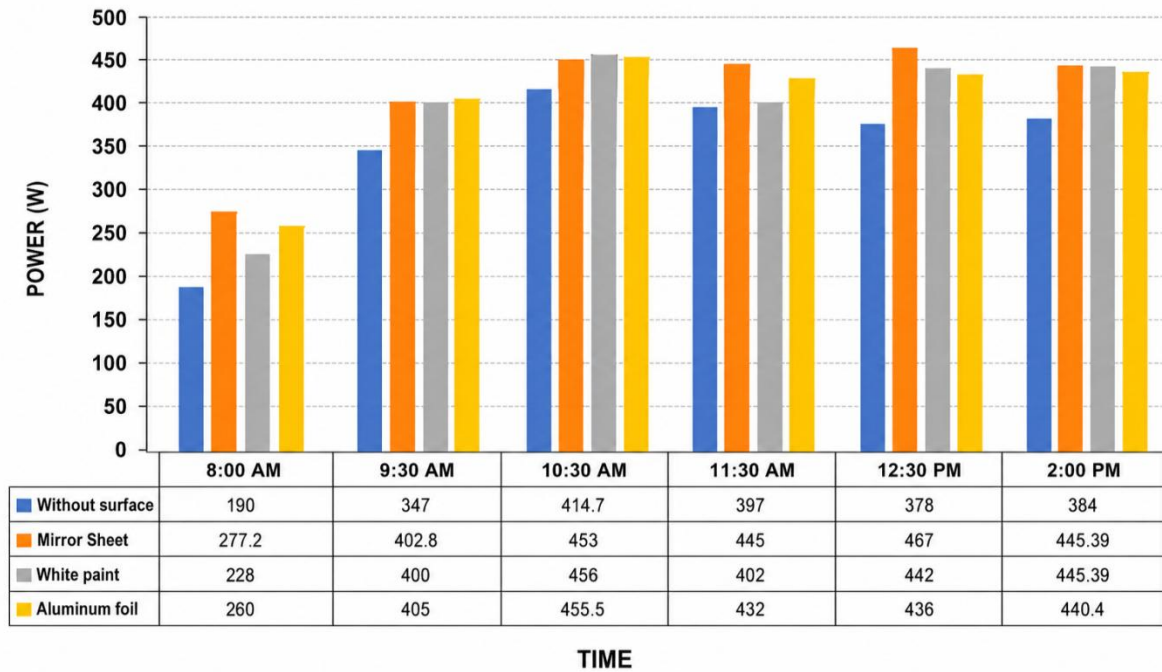


Fig 7 . Comparison of output power under different rear-side reflective surfaces.

The impact of the surface reflectivity of the rear side on the bifacial PV module's output power is clearly seen in the experimental results. The reference configuration with a non-reflective surface, a white-painted surface, a silver-painted surface, and aluminum foil are some of the configurations on the rear side that compared to the measured output power of the bifacial PV module. The reference configuration had the lowest rear surface irradiance contribution.

During the entire process of measurement, aluminium foil continuously exhibited the highest power output compared to other surfaces under evaluation. This can be attributed to the high specular reflectance of aluminium foil that allows incident solar radiation to be rerouted onto the back surface of the bifacial surface. Meanwhile, lesser but consistent improvement was obtained using the diffuse reflection on the surface of the

white-painted surface. Similarly, notable improvement was observed from the silver-painted surface. This is consistent with the rear-side irradiance model presented in Section 6 that the improved energy conversion and increased irradiance on the rear side of surface elements are directly proportional to the surface albedo.

5.3. Quantitative Performance Comparison

Quantitative evaluation of the enhancement of power generation of the bifacial solar module with different reflective sheets at the back side was determined. Electrical measurements such as voltage, current and output power were observed on each reflector configuration, i.e. mirror, aluminium sheet and white-painted surface. The findings suggest that reflective surfaces are very effective to increase the overall energy generation and irradiance at the back. The mirror reflector amplified the power output the most of the surfaces that were tested, then the aluminium and finally the white paint. This comparative analysis indicates the efficiency of rear-side reflection in maximizing the working of the bifacial PV systems.

Table V. Experimental Performance Comparison of Different Rear-Side Reflective Materials.

Reflective Material	Reflectivity (ρ)	Rear-Side Irradiance Gain (%)	Power Gain (%)	Overall Performance
Mirror	0.90–0.95	25–35	18	Excellent
Aluminium Foil	0.65–0.80	15–22	14	Very Good
White Paint	0.75–0.85	18–25	8	Good

5.4. Power Gain Calculation

The percentage increase in output power due to rear-side reflective materials can be calculated as

$$\text{Power Gain (\%)} = \frac{P_{\text{reflector}} - P_{\text{reference}}}{P_{\text{reference}}} \times 100 \quad (18)$$

Where

- $P_{\text{reflector}}$ = power output with reflective surface (mirror, aluminium, or white paint)
- $P_{\text{reference}}$ = power output without rear-side reflector

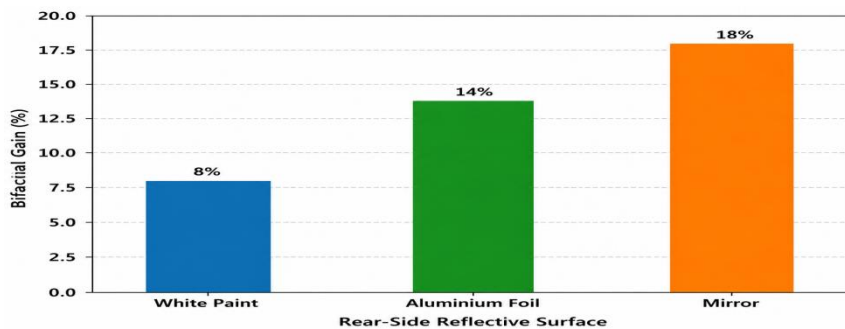


Fig 8 . Quantitative comparison of bifacial gain for different reflective materials.

In this work, the quantitative performance increase of a bifacial photovoltaic module using various rear-side reflective surfaces is measured for EV charging applications. The materials tested were white paint, aluminum foil, and mirror sheet against a non-reflective reference case. Based on the data, the average bifacial gains stand at 18% for mirror surfaces, 14% for aluminum foil, and about 8% for white paint. Aluminum foil supplied a reasonable trade-off between cost and performance, while the mirror's sharp specular reflection gave

the most boost. Increased PV output under MPPT control enhances the EV charging efficiency. Considering all the factors, bifacial photovoltaic performance is enormously enhanced by rear-side optimization.

5.5. Impact on EV Battery Charging Performance

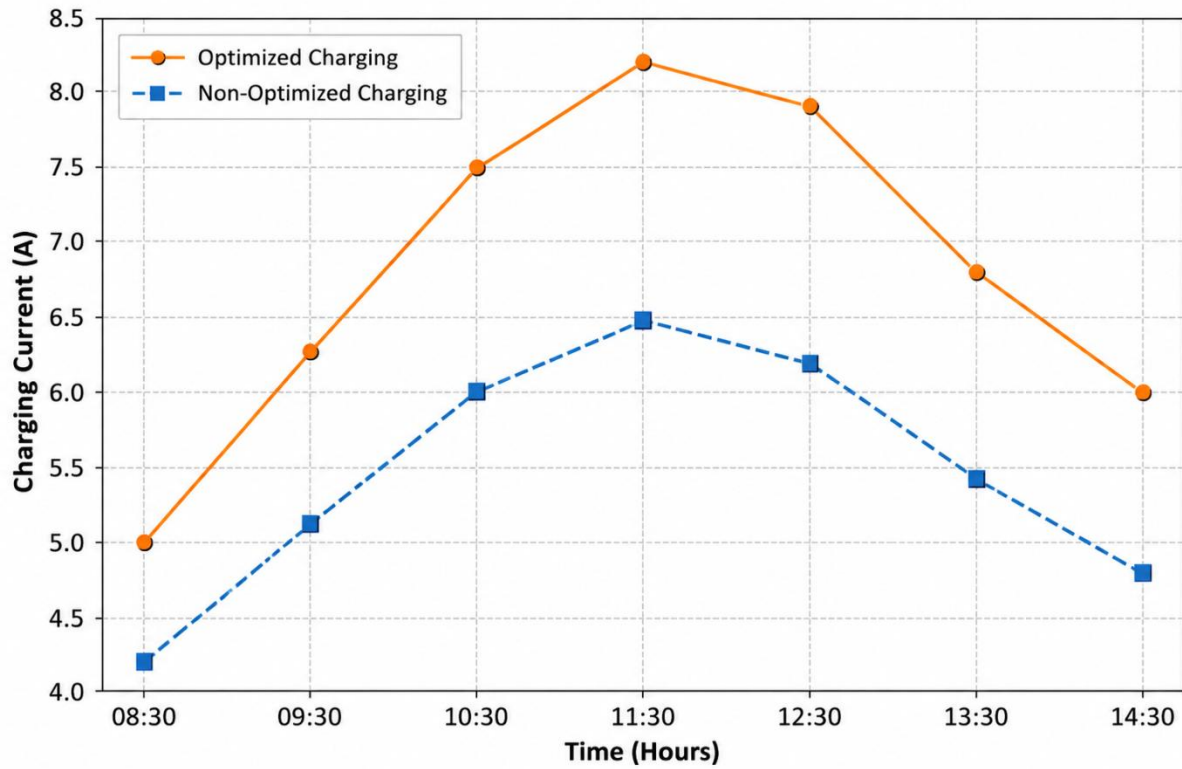


Fig 9. EV battery charging current profile with and without rear-side optimization.

The best performing reflecting surface was integrated into the MPPT-based charging system to evaluate the effect of optimization on the efficiency of an electric vehicle (EV) battery charging process. Figure Y shows the battery voltage profile as well as the charging current measurement process. From the optimized and non-optimized bifacial arrangements, the optimized arrangement had higher current levels as compared to the non-optimized arrangement.

Temperature and irradiance fluctuations were not effective enough to prevent the MPPT controller from operating near the maximum power point. The accessible power from PV as a direct outcome of increased rear side irradiance led to improved charging efficiency and current stability. This shows that optimizing from behind improves PV output and hence the efficiency of solar-powered EV charging systems.

5.6. Thermal and Environmental Considerations

Excessive thermal increase due to this was prevented with the elevated mounting structure, thus allowing airflow around the bifacial module. Enhanced surfaces, on the one hand, increased irradiance on the rear side, but it was observed during this trial that there was no negative effect on thermal performance. Therefore, it can be noted that no detrimental effect occurs when there are augmentations on the rear side of a module.

The extent of bifacial gain was also managed by appropriate environmental variables such as surface cleanliness, diffuse irradiance amount, as well as sun angle. These findings emphasize the necessity of environmental factors while selecting rear-side reflective materials.

5.7. Discussion and Practical Implications

From the experimental results, it can be noted that bifacial PV performance enhancement for EV charging can be attained using a cost-effective reflecting surface. As far as peak power gain is concerned, aluminum foil material has shown better results. However, issues such as those related to maintenance and

durability need to be fixed so that this material may be used practically. Although using diffuse reflectors such as surfaces with a white finish has lower efficiency, they are easy to maintain.

Overall, with all factors taken into consideration, the findings are as per the desired performance parameters for the theory and validate that the bifacial PV technology indeed has a high potential to enhance energy efficiency when integrated with MPPT chargers for EVs. The proposed method is a good solution for decentralized EV charging infrastructure, which is sustainable and scalable.

For bifacial PV systems, the choice of the reflector on the back should consider the following factors: Power enhancement, installation area, cost, durability, maintenance. The mirror is recommended for applications on residential rooftop and domestic installations, where a large power gain and high rear-side irradiance can be obtained in a small installation space. Aluminium foil is an economical choice of material for large deployments where reflective performance is required, but investment is a key concern for the commercial sector. White Paints/High-Albedo Coating can give relatively uniform diffuse reflectivity over large areas, but requires a higher up-front investment and maintenance/recoating of the surface over time, for large-scale PV installations.

The ideal solution is mirror for maximum performance, aluminium foil for commercial applications for best cost performance and white paint for large-scale applications with an emphasis on uniform coverage at higher investment.

Table VI. Comparative characteristics of rear-side reflective surfaces for bifacial photovoltaic applications.

Parameter	Conventional High-Albedo Surface	White Paint	Aluminium Foil	Mirror
Reflection	Mostly diffuse	Mostly diffuse	Mixed diffuse/specular	Specular
Direction of reflected light	Many directions	Many directions	Moderately directional	Narrow direction
Sensitivity to sun position	Low–moderate	Low–moderate	Moderate–high	Very high
Rear-side uniformity	Better	Better	Moderate	Potentially poor
Tracking required	Usually no	Usually no	Usually no	May be required
Cleaning requirement	Moderate	Low–moderate	High	High
Risk of hot spots	Low	Low	Moderate	Higher
Bifacial application	Common	Common	Experimental	Experimental
Relative reflectivity	Moderate–high	High	High	Very high
Cost	Low–moderate	Low	Low	High
Durability	High	Moderate	Moderate	High, but fragile
Main advantage	Uniform rear illumination	Low-cost and simple implementation	Low-cost high-reflectivity option	Maximum directed rear-side irradiance
Main limitation	Lower reflection than mirror	Surface degradation over time	Wrinkling, oxidation and soiling	Glare, hot spots and alignment sensitivity

6. CONCLUSION

In this study, a 545 W bifacial photovoltaic (PV) module coupled with a maximum power point tracker (MPPT) charge controller was tested for EV charging through optimization of the reflective surfaces on its rear side under a wide variety of outdoor illumination conditions. The non-transparent materials such as mirror, aluminium foil and white-painted surfaces were tested in order to enhance the rear-side irradiance. The best overall power gain (18%) was obtained for the mirror, followed by aluminium foil at 14% and white paint at about 8%. This greater performance was attributed to the greater specular reflectivity of the mirror, which

concentrated the solar radiation to the back surface of the bifacial module. Aluminium foil made a big difference in terms of low cost improvement, followed by a smaller but consistent improvement from white paint.

The MPPT controller also enhanced the charging performance by offering more charging current and stability under various irradiance levels. The greater rear-side illumination led to greater PV power output which was successfully tapped for EV battery charging. In conclusion, the results showed that, overall, rear-side reflective surface optimization is a viable and practical approach to enhancing bifacial PV performance without adding extra PV modules or significant changes to the system design. The tested material that yielded the highest power gain was the mirror with 18% power gain, which would be the most practical material to enhance the performance of solar-powered EV charging.

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