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Eco-Friendly Charging Systems Using Solar Energy for Electric Vehicles

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ABSTRACT: The advancement of innovative EV chargers is essential for boosting the adoption of electric vehicles, alleviating range anxiety, and promoting technological breakthroughs that improve charging efficiency and grid integration. These developments tackle current issues and support a more sustainable and convenient future for electric mobility. This paper examines the performance characteristics of a solar-integrated charging system. It describes a simulation study on utilizing solar energy as the main direct current (DC) source for EV charging. The method includes an Energy Storage System (ESS) to manage solar energy fluctuations and reduce photovoltaic (PV) mismatch losses. Developed using MATLAB, the system integrates key components such as solar PV panels, the ESS, a DC charger, and an EV battery.

The study reveals that an increase in solar irradiance from 400 W/m² to 1000 W/m² led to a significant 47% rise in the output power of the solar PV system. Concurrently, the ESS exhibited a 38% increase in output power under the same conditions, with tests conducted at a room temperature of 25°C. The findings highlight that optimal placement of solar panels with higher irradiance levels is crucial for maximizing the efficiency of integrated solar energy EV chargers. The research also demonstrates a positive correlation between higher irradiance levels and the State of Charge (SOC) of the EV battery. This correlation underscores the potential efficiency improvements through enhanced solar energy absorption, leading to more efficient and faster EV charging.

I. INTRODUCTION

The rapid shift towards sustainable energy is only achievable through the large-scale adoption of Electric Vehicles (EVs) [1,2]. EVs provide a cost-effective and eco-friendly alternative to traditional fossil fuel-powered vehicles, significantly reducing carbon emissions compared to fuel cells or conventional transport options. Nonetheless, for EVs to become widely adopted, a simple and robust charging infrastructure is necessary, with a particular focus on Direct Current (DC) chargers to ensure efficiency, reliability, and accessibility [3]. DC chargers offer low-loss, efficient, and quick charging capabilities for modern electric transportation, unlike Alternating Current (AC) chargers. However, the widespread installation of chargers on the already strained power grid is not feasible. Consequently, DC chargers powered by renewable energy sources have emerged as a viable solution. Solar energy, in particular, presents an innovative approach to EV charging [4,5]. Solar power, derived from sunlight, provides a plentiful and clean energy source, making it an ideal solution for sustainable EV charging [6]. However, the intermittent nature of solar energy and photovoltaic (PV) losses pose significant challenges to the adoption of this technology for DC chargers.

The Energy Storage System (ESS) has also emerged as a viable charging solution. When paired with solar energy, ESS ensures clean, reliable, and efficient charging for EVs [7,8]. This combination frees EV owners from relying solely on the traditional power grid, while also contributing to environmental conservation and fostering energy self-sufficiency. Integrating solar energy, ESS, and DC charging involves significant research and development challenges, particularly regarding compatibility and energy flow management [9]. The proposed system promotes sustainability and supports decentralized energy generation, enabling consumers to manage their energy needs.

Recent literature provides a foundation for this research, with numerous articles discussing solar energy, EVs, and charging infrastructure [10]. However, most of these works focus on individual components, missing the potential of an integrated system [11]. Research on DC fast chargers typically addresses the technical requirements for efficient EV charging, yet few studies have combined these with renewable energy sources. Similarly, studies on ESS often emphasize grid applications, overlooking their critical role in a decentralized, renewable energy setup for EVs [7]. Some research has explored integrating solar power and ESS in EV charging systems, but these studies often lack a comprehensive

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approach that includes DC chargers, PV-induced losses, energy management, and automation, thus leaving a gap in the literature [12,13].

In photovoltaic (PV) systems, mismatch losses can significantly reduce efficiency. These losses arise when PV modules within an array do not perform identically, a common issue in extensive solar arrays. The evaluation of mismatch losses involves comparing the expected power output of uniform PV modules with the actual output recorded from the system [14]. Several factors contribute to these losses, including variations in module manufacturing, effects of shading, accumulation of dirt, and temperature disparities. Additionally, complications such as faulty electrical connections, misalignment of cells, surface contamination, inconsistencies in module orientation, and varying temperature coefficients exacerbate the problem [15]. The manufacturing of PV cells is a complex process that involves multiple stages, which can lead to inconsistencies in cell properties such as doping, further leading to discrepancies at the cell level [16]. When these panels are configured into an array, these mismatches can intensify. For instance, a 0.1% mismatch loss in an array producing 1000W would result in a loss of 1W (0.1% of 1000W). Understanding and quantifying these losses are crucial for enhancing the overall efficiency of PV systems.

This study seeks to mitigate these inefficiencies by integrating and optimizing key components to maximize system efficiency and promote sustainability. It makes a substantial contribution to renewable energy and electric mobility sectors by proposing a comprehensive, grid-independent solution that encompasses solar power, Energy Storage Systems (ESS), and efficient Electric Vehicle (EV) charging stations. The research not only offers a blueprint for a self-sufficient energy model but also pioneers new pathways for sustainable transport and energy management. Beyond theoretical exploration, this research provides a practical and eco-friendly approach for EV charging, marking a progressive step towards innovative energy utilization.

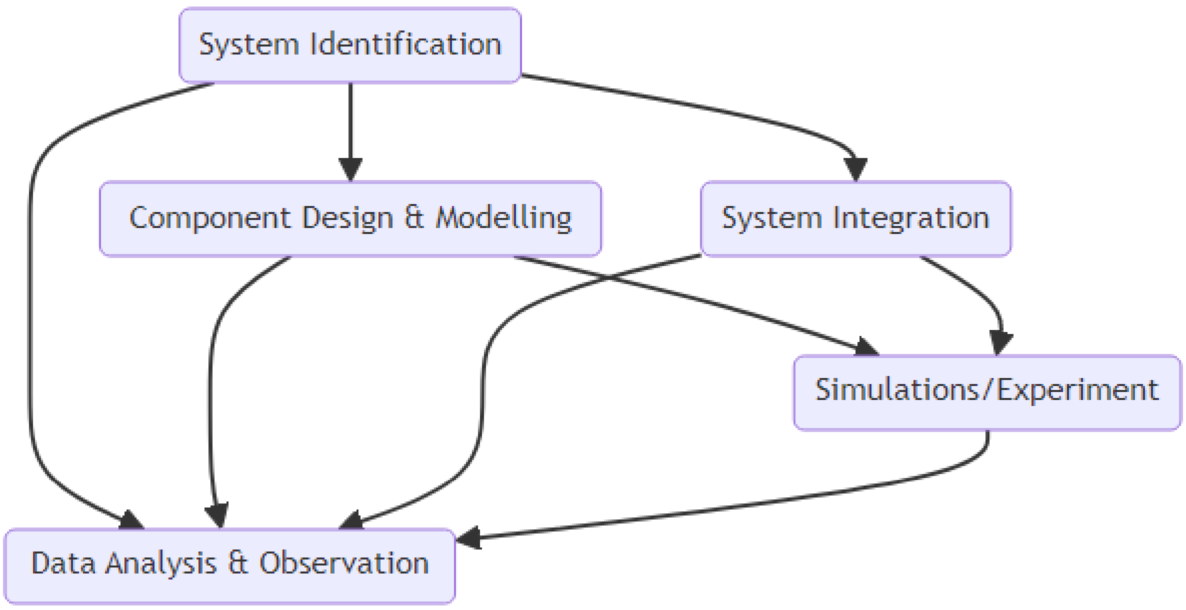

Figure 1. General structure diagram for the system.

II. METHODS

As depicted in Figure 1, our study initiates by identifying the components of the innovative PV-ESS integrated system. The process begins with the identification of components, followed by the design and modeling of each individual component. Subsequently, these subsystems are integrated into a comprehensive system. Simulations are then conducted on this integrated system, leading to the analysis of results. This sequence culminates in a thorough data analysis after the successful integration of all individual components, providing insights that significantly enhance the system's overall functionality and potential for application.

Figure 2 illustrates the designed system which focuses on harvesting and storing solar energy for electric vehicles (EVs). The system is primarily composed of a PV array, a Maximum Power Point Tracking

(MPPT) front-end converter, an energy storage battery, and a charging DC-DC converter. This system addresses intermittent factors like partial shading and PV mismatch losses by dynamically adjusting the operational point of the PV array to optimize power transfer into the ESS battery [17]. Additionally, the integration of EV batteries simulates a practical scenario for charging EVs.

Lithium-ion batteries are the choice for both EVs and ESS due to their high energy density, longevity, and cost efficiency. Nonetheless, a sophisticated Battery Management System (BMS) is essential to monitor and regulate various attributes of the battery during charge and discharge cycles. Accurately measuring the State of Charge (SOC) of lithium-ion batteries presents challenges due to their highly time-varying behavior, complex electrochemical properties, and overall intricacy. The SOC is crucial as it indicates the degree to which the battery is charged or discharged, assessing its operational status and estimating its remaining lifespan.

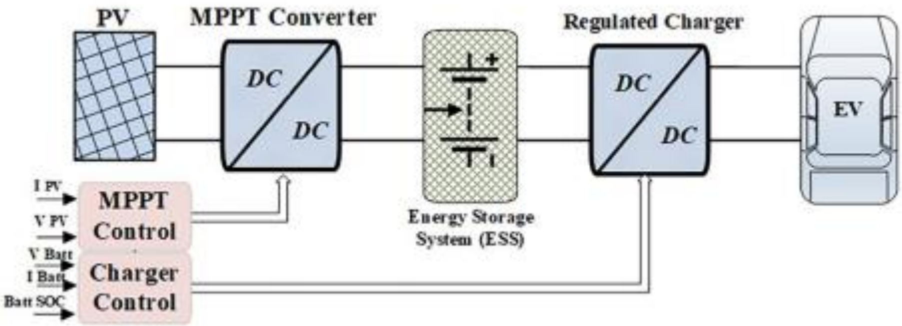

Figure 2. Elements of the charging system and mutual integration

MATLAB offers advanced models for simulating the dynamics of lithium-ion batteries. These models incorporate multiple parameters such as voltage, current, temperature, and capacity, providing a detailed depiction of battery behavior. The models account for the non-linear and time-variant characteristics of the batteries, enabling precise estimations of the State of Charge (SOC) across various operating conditions. This level of precision is vital for optimizing charge and discharge strategies, improving the efficiency of electric vehicles (EVs) and energy storage systems (ESSs), and ensuring the durability of lithium-ion batteries.

The design process of the simulation model is executed in two main stages. Initially, each element is modeled individually, taking into account its electrical characteristics and performance parameters. This thorough approach ensures that the unique attributes of each component are accurately represented. Subsequently, the model integrates all elements into a unified circuit. This integration is meticulously done to consider the interactions and connections among the components, which helps in achieving seamless and efficient functionality of the overall system.

The effects of increased solar radiation and temperature variations on the output of photovoltaic (PV) panels and their subsequent impact on the State of Charge (SOC) of electric vehicle (EV) batteries were explored using MATLAB simulations. The dynamic model employed consists of interconnected blocks representing a proposed EV charger powered primarily by solar energy. The "Irradiance Source Block" in MATLAB provides the functionality to input a time-varying irradiance profile, utilizing a general PV profile that reflects a typical solar day.

The duration of daylight hours varies based on geographic location, time of year, and local weather conditions. It's essential to acknowledge that while the sun may be above the horizon for approximately 12 hours, the intensity of sunlight fluctuates throughout the day. Peak sun hours, which are the times when the sun's intensity is adequate for solar panels to function at optimal efficiency, are typically considered to be between 5 to 6 hours per day in preliminary simulations. Non-peak sun hours signify periods of lower solar intensity and consequently reduced energy production.

Additionally, the simulation incorporates a "Temperature Source Block" to account for the effects of temperature variations on PV modules. These temperature fluctuations can significantly influence PV efficiency. Nonetheless, the energy buffering capability of the Energy Storage System (ESS) within the proposed setup ensures that EV charging remains consistent despite these variations. The "PV Array Block" provides detailed modeling features, simulating the array’s response under varying irradiance and temperature conditions, which aids in understanding the impact of high radiation on PV output and analyzing mismatch losses.

Furthermore, a separate "Mismatch Model Block" in MATLAB implements the mathematical model for mismatch losses, while the "MPPT Controller Block" executes the simulations' maximum power point tracking using the perturb and observe (P&O) algorithm. This comprehensive approach to simulation offers a deep insight into optimizing solar energy utilization for EV charging under variable environmental conditions.

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The operational point of the PV system is dynamically adjusted to optimize power output in the simulations. The analysis also incorporates the use of the "Data Logging Block," which is essential for recording all the time-varying variables such as PV voltage and current, charging voltage and current, output power, solar irradiance, and the State of Charge (SOC) of the EV battery. These variables are concurrently displayed for real-time observation and analysis through the "Scope Block". This feature facilitates a comprehensive monitoring and diagnostic approach, allowing for an in-depth evaluation of system performance under various conditions.

III. SYSTEM SPECIFICATIONS

The chosen simulation model features the JKM380M-72-V solar module from JinkoSolar Co., Ltd, renowned for its superior efficiency and seamless integration with system components. This model explored solar irradiance levels from 400 W/m² up to 1000 W/m², increasing incrementally by 50 W/m² while keeping the temperature constant at 25˚C. The influence of temperature variations on the Energy Storage System (ESS) output was thoroughly examined across a range of temperatures: 5˚C, 15˚C, 25˚C, 35˚C, and 45˚C, with detailed specifications provided in Table 1.

The ESS employs a lithium-ion battery with a nominal voltage of 600V and a capacity of 200Ah. Initial SOC was set to 100%, and the response time fine-tuned to one second. Figure 3 displays the discharge behavior of the ESS battery under various conditions.

Further, the setup includes a 6 kW photovoltaic (PV) array coupled with a robust 30 kW DC charger that delivers an output voltage ranging from 200 to 700VDC and a current of 100A, effectively simulating fast charging scenarios. The EV battery specifications include a capacity of 40 kWh, a voltage of 350V, and an energy capacity of 114Ah. The model also incorporates a buck-boost converter circuit, detailed in Figure 4, critical for managing the power conversion within the system.

All these components and their interactions are meticulously captured in Table 2, which details the overall system parameters utilized in simulations and discussions. This comprehensive setup provides an accurate reflection of the energy management and conversion dynamics essential for real-world applications.

IV. MATHEMATICAL CALCULATION

To determine the charging time required for an Energy Storage System (ESS) using a photovoltaic (PV) array, we use the battery's capacity, which is central to calculating the duration. The calculation is based on the equation:

Let:

-V represent the voltage of the ESS (in volts),

- C represent the rated capacity of the battery (in ampere-hours),

- k be the conversion factor from watt-hours to kilowatt-hours (usually 1000 to convert from Wh to kWh).

Then, the equation for calculating the total energy capacity of the battery in kilowatt-hours (kWh) can be written as:

$$\text{Total Energy Capacity} = \frac{V \times C}{k} \tag{1}$$

Substituting the specific values you have:

$$\text{Total Energy Capacity} = \frac{600 \times 200}{1000} = 120\ \text{kWh}$$

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Table 1. Parameters for Solar Panels

Parameters	Values
MaximumPower (W)	380.295
Cellspermodule (Ncell)	72
Open circuit voltage Voc (V)	48.9
Short-circuit current Isc (A)	9.75
Voltage at maximum power point Vmp (v)	40.5
Current at maximum power point Imp (A)	9.39
Temperature coefficient of Voc (%/deg.C)	-0.326
Temperature coefficient of Isc (%/deg.C)	0.055005

This table lays out the key parameters of solar panels, including their power capacity, voltage, current specifications, and temperature coefficients, which are essential for evaluating their performance under different conditions.

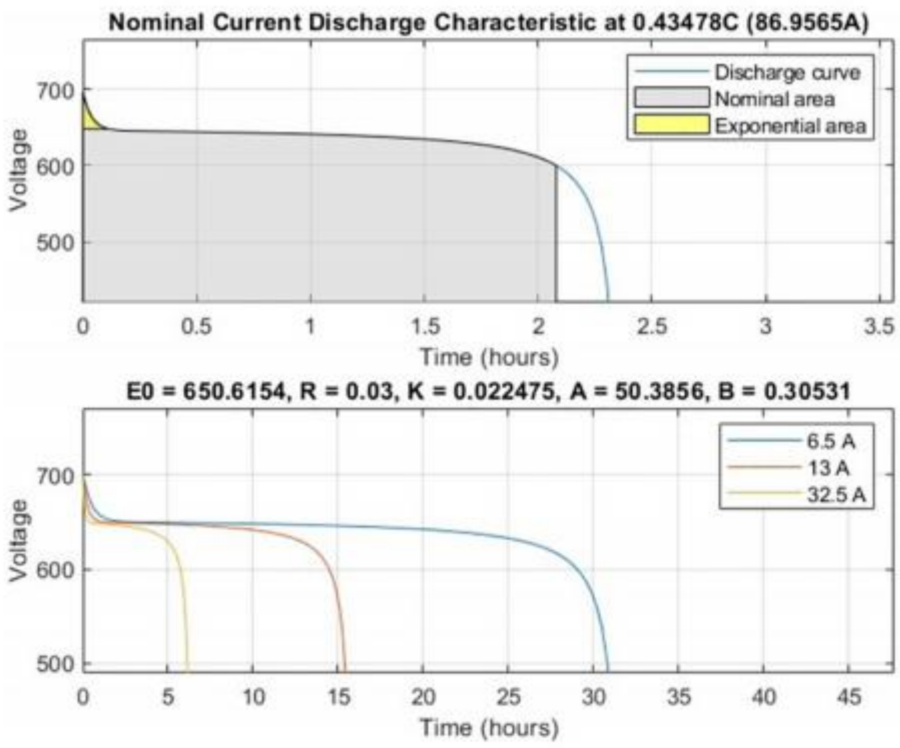

Figure 3. Time-dependent discharge curve for ESS

The calculation for the time required to charge an Energy Storage System (ESS) is formulated as follows:

$$\text{ESS Charging Duration} = \frac{\text{Total ESS Energy Capacity}}{\text{Power from PV Array}} \quad (2)$$

Where the total energy capacity of the ESS is 120 kWh and the output from the PV array is 6 kW, the time needed to fully charge the ESS is:

$$\text{ESS Charging Duration} = \frac{120 \text{ kWh}}{6 \text{ kW}} = 20 \text{ hours}$$

For an ESS that is completely depleted, it would take about 20 hours to fully recharge using a 6 kW PV setup, assuming it restores the ESS to a full 100% SOC. As for an Electric Vehicle (EV) battery connected to a 600V and 200Ah ESS, the charge duration depends on the supply capability of the DC charger and the maximum power intake the EV battery can manage. The formula for calculating the maximum charging power that can be delivered to the EV battery is:

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$$\text{Max. Char. Power} = \min(\text{DC Char. Outt, EV Bat. Volt} \times \text{Max EV Bat. Curr}) \quad (3)$$

This equation helps determine the feasible charging power considering the constraints of both the charger's output capacity and the battery's maximum current acceptance level.

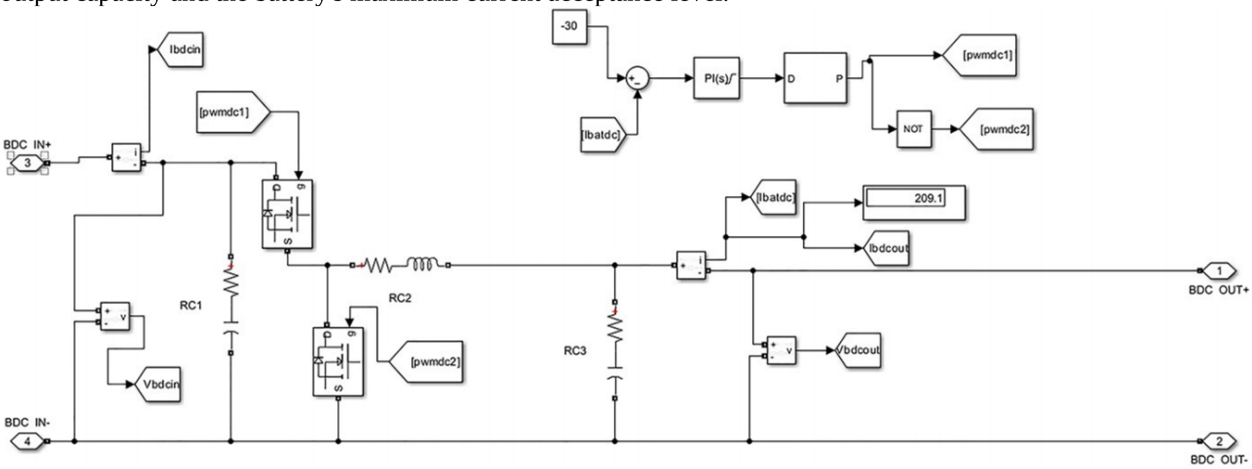

Figure 4. Buck-boost converter in Matlab.

Table 2: Parameters for the PV-ESS DC Charger System

Parameters	Values
ESS BatteryType	Lithium-ion
ESS NominalVoltage	600 V
ESS RatedCapacity	200 Ahor 120 kW
Initial SOC for ESS Battery	100%
ESS ResponseTime	1 second
PV ArrayPower	6 kW
DC ChargerPower	30 kW
DC Charger Output Voltage Range	200–700 V DC
DC Charger Max Output Current	100 A
EV BatteryCapacity	40 kWh
EV BatteryVoltage	350 V
EV BatteryEnergy	114 Ah

The above table outlines the key specifications of the integrated PV-ESS DC charger setup, including battery type, capacity, charger power, and more.

The charging power for the EV battery is determined by the lesser of the output of the DC charger or the product of the EV battery's voltage and maximum current, calculated as follows:

$$\text{Charging Power} = \min(30\text{ kW}, 350\text{ V} \times 100\text{ A}) = 30\text{ kW} \quad (4)$$

Using the charging power, the time required to fully charge the EV battery can be calculated by:

$$\text{Charging Time for EV} = \frac{\text{EV Battery Capacity}}{\text{Charging Power}} = \frac{40\text{ kWh}}{30\text{ kW}} = 1.33\text{ hours} \quad (5)$$

These parameters and calculations provide a detailed view of the system's capabilities and efficiency in utilizing photovoltaic energy for charging purposes.

For the system configured with a 6 kW photovoltaic (PV) array, the expected charging duration for the Energy Storage System (ESS) is projected to be around 20 hours. By contrast, charging the electric vehicle (EV) battery, which has a capacity of 40 kWh, would significantly take less time. Utilizing a 30 kW DC charger equipped with a voltage range of 200–700 V and a maximum output current of 100 A, the EV battery could be

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fully charged in approximately 1.33 hours. This highlights the efficiency and rapid charging capabilities provided by the higher-power DC charger in comparison to the more extensive charging time required for the ESS under a smaller PV array capacity.

V. RESULTS AND DISCUSSION

Solar irradiance, defined as the solar power per unit area received, varies based on geographic location, time of day, seasonal shifts, and atmospheric conditions [18,19]. Our analysis shows a significant linear increase in the output power of solar panels—by 47%—as solar irradiance escalates from 400 W/m² to 1000 W/m². This relationship between solar irradiance and panel output is strongly linear, demonstrated by an \(R^2 \) value of 0.98393, as illustrated in Figure 5. Such findings emphasize the importance of positioning solar panels in areas that receive maximal sunlight exposure.

The direct correlation observed between increasing output power and higher solar irradiance levels supports the principle that more sunlight translates to enhanced power output [18]. Conversely, reduced irradiance leads to a decrease in power generation, primarily because fewer photons hitting the solar cells result in less electron activity, thus lowering the generated current and power [20]. Additionally, given that solar cells respond to specific light wavelengths, changes in the spectral composition of sunlight can also affect their operational efficiency [21].

While this study has controlled the temperature at a constant 25°C, it's crucial to note that typically, higher sunlight exposure can also lead to increased temperatures, potentially impacting the efficiency of solar panels. This aspect might require further exploration, particularly in designs like your interest in sustainable development and renewable energy technologies, which could benefit from understanding these nuanced interactions for more efficient system designs.

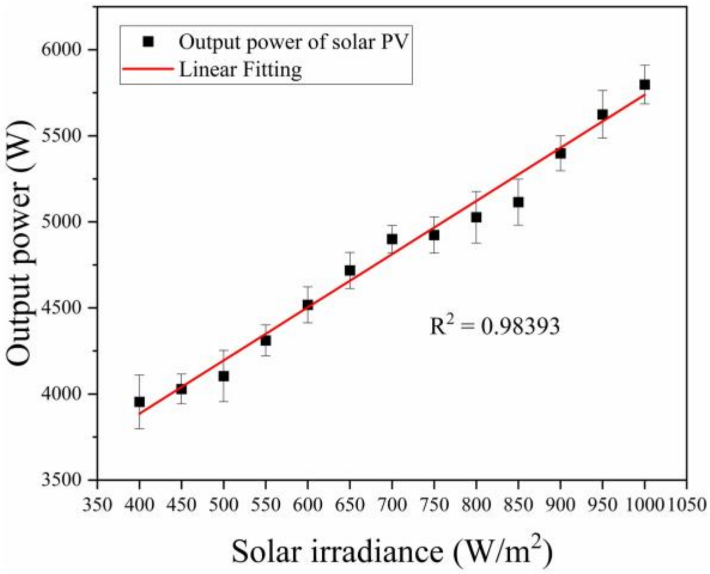

Figure 5. The relationship between solar PV output power and solar radiation

This observation is critical as solar cells typically become less efficient at higher temperatures—a scenario that could potentially negate the benefits derived from increased irradiance [22]. A significant finding from the research is the measurement of the solar panel's output power under an irradiance of 1000 W/m² at a stable temperature of 25°C. The results indicated a peak output power of 5799 W, accompanied by an output voltage of 311.2 V and an output current of 18.78 A. These specific measurements offer a clearer understanding of the direct relationship between solar irradiance and the performance characteristics of solar panels.

This detailed data highlights how solar panel efficiency can be maximized under optimal conditions of irradiance and temperature, providing valuable insights for the design and placement of solar energy systems to achieve the best possible performance.

The process of harnessing energy from solar panels involves the use of a Maximum Power Point Tracking (MPPT) system, which directs the power before it is stored in the Energy Storage System (ESS). Due to inherent fluctuations in solar panel output caused by variations in sunlight intensity, temperature, and other environmental factors, maintaining peak efficiency consistently is challenging. The MPPT system plays a crucial role in mitigating these issues by continuously monitoring and adjusting the voltage and current of the solar panels to ensure they operate at their most efficient point [23].

After the MPPT optimization, the output power from the solar panels increased to 6.45 kW, marking an 11.2% enhancement in performance. This improvement was observed under optimal conditions, with a solar irradiance of 1000 W/m² and a panel temperature maintained at 25˚C. This illustrates the effectiveness of the MPPT in optimizing solar panel performance, thus maximizing the amount of energy captured and subsequently stored in the ESS, which is essential for efficient EV charging.

This slight 0.14% reduction in the State of Charge (SOC) of the Energy Storage System (ESS) can largely be traced back to minor losses that occur during the conversion process. These losses are inherent when DC-DC converters, utilized within the MPPT (Maximum Power Point Tracking) system, are employed to synchronize the voltage levels between the solar panels and the battery [24]. Although these losses are relatively small, they are significant enough to cause a minor decrement in the ESS's SOC.

The system comprising the solar panel, MPPT, and ESS forms a cohesive unit designed to capture and store solar energy with optimal efficiency, ensuring that this energy remains readily available for future use. The integration of these components is vital for maximizing the effectiveness and overall efficiency of the solar energy system, allowing it to provide a reliable source of energy for EV charging and other applications. This integrated approach not only enhances energy capture but also minimizes energy wastage, thus supporting sustainable energy solutions.

Figure 7 illustrates the correlation between solar irradiance and the average output power of the Energy Storage System (ESS) at varying solar temperatures of 5˚C, 15˚C, 25˚C, 35˚C, and 45˚C. As solar irradiance increases, so does the ESS's output power across all temperatures, a trend paralleling the rise in solar panel power output shown in Figure 5. However, the State of Charge (SOC) of the ESS remains stable at 99.85% irrespective of changes in irradiance, indicating efficient energy utilization up to its full storage capacity [22, 25].

A notable increase in solar irradiance from 400 W/m² to 1000 W/m² results in a 38% rise in ESS output power at a constant temperature of 25˚C, which is 9% less than the increase seen in solar panel output. This discrepancy may stem from reduced effectiveness of the MPPT system at higher irradiance levels and other factors like battery charging efficiency and voltage conversion losses [22, 25].

Additionally, data suggest that the average output power of the ESS declines with increasing solar temperatures. This decrease is attributed to the reduced capability of solar panels to convert sunlight into electrical energy at higher temperatures [26]. Factors contributing to this efficiency loss include a decrease in the open-circuit voltage and potential thermal annealing in the panels, which can reduce performance and increase physical stress on the system [27, 28].

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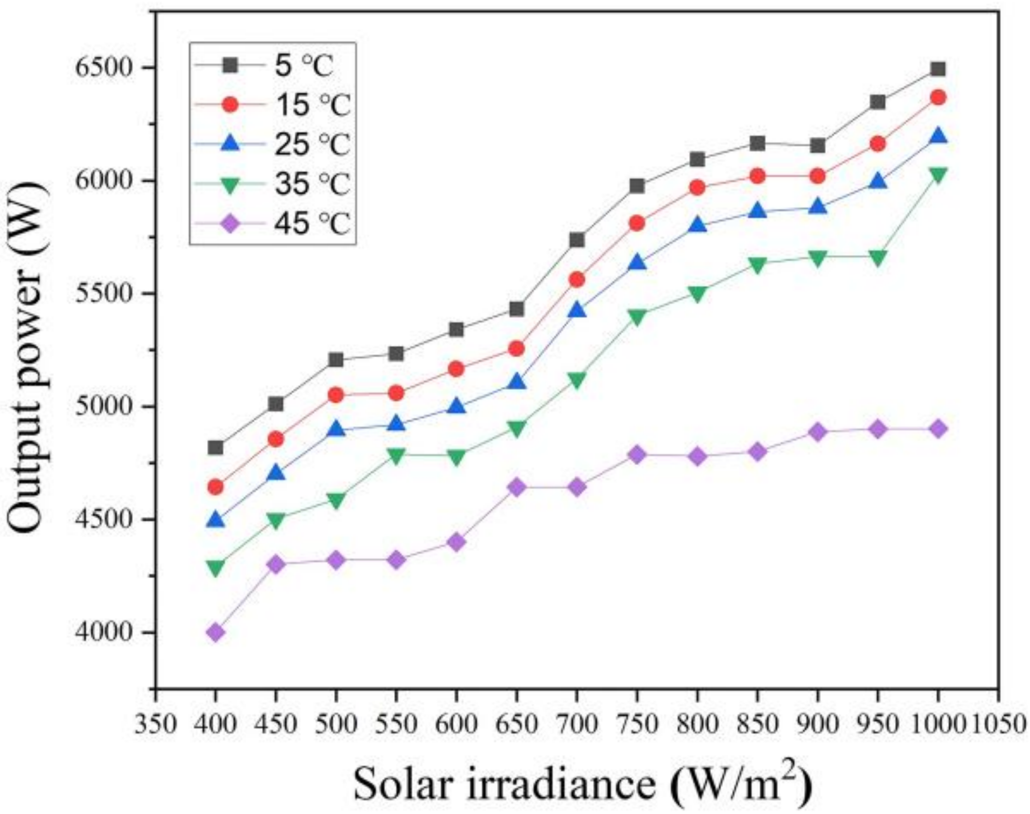

Figure 7. Correlation graph of ESS output power oaris with solar irradiance levels.

For the Energy Storage System (ESS), the average output power at a low temperature of 5˚C sees a 24% increase when solar irradiance rises from 400 W/m² to 1000 W/m². In contrast, at a higher temperature of 45˚C, the average output power of the ESS also rises but by a lesser 13%. The reduced rate of increase at 45˚C compared to 5˚C is attributed to the diminished power generation of solar panels at higher temperatures, which results in slower charging speeds [29]. Consequently, less electrical energy is available for storage in the ESS, and there may be a need to supplement power from other sources.

While higher irradiance levels can enhance output power, these gains are potentially negated by the losses incurred at elevated temperatures. The temperature coefficient of the solar panels plays a critical role in determining the net effect on system performance, influencing how efficiently the system operates under varying environmental conditions.

This investigation into an integrated solar system for EV charging, while comprehensive and backed by simulation-based analysis using MATLAB, presents certain constraints. The reliance on MATLAB simulations to evaluate system performance is beneficial for conceptualizing ideal scenarios but may not fully encapsulate the complexities of real-world environments. Such simulations often fail to account for varying environmental conditions, operational fluctuations, and material discrepancies, which can significantly affect system behavior.

Moreover, the research methodology employs a constant temperature setting of 25˚C to analyze the influence of solar irradiance on the EV battery. This approach does not consider variable weather conditions such as rain or cloud cover, nor does it factor in different levels of humidity. These oversights could lead to a disparity between simulated results and actual system performance in diverse environmental settings.

The scope of the study is also limited by its specific focus on solar irradiance levels from 400 W/m² to 1000 W/m², neglecting to explore the potential impacts of other solar panel types or different battery conditions within the ESS. Additionally, the study does not address the effects of deep discharge cycles or cyclic stress on long-term battery health, which are crucial factors for sustainable energy storage solutions.

Another significant limitation is the assumption of consistent efficiency across electrical components, such as DC-DC converters and the MPPT system. The efficiency of these components may vary with different operational conditions, potentially impacting the overall system performance. The study's assumption of a static MPPT efficiency disregards possible variations that could arise from changing solar irradiance levels or other operational dynamics. This could lead to inaccuracies in understanding the full capabilities and limitations of the solar charging system.

VI. CONCLUSION

Emerging novel EV chargers and comprehensive energy management strategies are essential for advancing a sustainable and integrated future. These chargers necessitate a ubiquitous charging infrastructure with universal compatibility and the ability to offer rapid, off-grid charging options. Addressing these challenges is key to accelerating the adoption of electric vehicles. This paper presents a pioneering integrated PV-ESS system designed to enhance fast charging for electric vehicles. The system mitigates issues associated with solar variability by channeling surplus solar power into an energy storage system (ESS). This stored energy is then efficiently deployed for EV charging, reducing reliance on the electrical grid and decreasing mismatch losses. The system incorporates an MPPT in a front-end converter to maximize the utility of the PV array, while a secondary DC-DC converter manages the EV charging process. A conceptual model is discussed where a 6 kW solar panel system charges a 200 Ah ESS, which in turn can fully charge a 40 kWh EV in just 1.33 hours.

Research outcomes demonstrate a clear relationship between increased solar irradiance and enhanced solar panel output, emphasizing optimal solar panel placement for maximum efficiency. Additionally, the study shows that with an increase in solar irradiance from 400 W/m^2 to 1000 W/m^2, there is a 47% rise in solar panel output power, with the ESS experiencing a slightly lower 9% increase. The findings establish a proportional relationship between solar irradiance and the SOC of the EV battery, indicating improved charging efficiencies correlating with higher irradiance levels.

This model exemplifies sustainable practices by leveraging renewable energy sources to reduce dependency on fossil fuels and decrease greenhouse gas emissions. However, shifting from traditional grid-dependent charging systems to a solar-based model poses significant challenges to the current power grid infrastructure, necessitating substantial modifications and possibly causing issues with grid stability. The limitations highlighted in this study call for further research and development to move from simulations to real-world applications. Future endeavors might include extensive testing under diverse environmental conditions, integration with existing grid infrastructure, and exploration of hybrid charging systems that combine solar power with other renewable energy sources. The potential benefits of this system in fostering a more sustainable and robust energy framework make it a valuable direction for future research and development.

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