International Journal of Electrical Engineering & Emerging Technology, Vol. 06, No. 02, DEC 2023, pp 11-20

A Techno-Economic Analysis of a Solar-Powered EV Charging Station in Pakistan

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[**Received on:** 10/05/2023 **Accepted on**: 13/11/2023 **Published on:** 01/12/2023]

Abstract **—The depletion of fossil fuel reserves and the urgent need to address climate change have propelled electric vehicles (EVs) to the forefront of sustainable transportation. However, for EVs to truly contribute to sustainability, they must be charged using renewable energy sources. This study focuses on the techno-economic analysis of a solar-powered EV charging station in Pakistan. Pakistan faces significant challenges in terms of carbon emissions, and this charging station has the potential to significantly reduce emissions and promote sustainable transportation. Through detailed power calculations, we determined that an MG ZS EV electric car in Pakistan requires a 10 kW solar system consisting of 25 solar panels occupying an area of approximately 7.804 m^2. The battery pack is composed of 2967 cells with 110 cells in series and 27 cells in parallel. A sensitivity analysis was conducted to assess the impact of various variables on the design of the solar-powered EV charging station. Our research demonstrates that the proposed solar-powered EV charging station offers a reliable and practical charging solution for EV owners in Pakistan. By utilizing renewable energy, this charging station can contribute to reducing carbon emissions and advancing sustainable transportation in the country.**

Index Terms—**Solar-powered EV charging station, Pakistan, techno-economic analysis, carbon emissions, sustainable transportation.**

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a key solution for combating climate change and reducing reliance on fossil fuels in many countries. However, developing nations such as Pakistan face challenges in establishing adequate charging infrastructure to support the widespread adoption of EVs. To address this issue, this research paper presents a techno-economic analysis of a solar-powered EV charging station specifically designed for Pakistan. By considering the performance factors of the solar system and battery pack, this charging station aims to facilitate the increased utilization of EVs in Pakistan.

The research conducted in this study is crucial in tackling the expected rise in energy consumption, particularly in the transportation sector, in Pakistan. Given Pakistan's abundant solar energy resources, leveraging solar power in the transportation sector can significantly reduce reliance on fossil fuels. Furthermore, the implementation of solar-powered EV charging stations contributes to the country's efforts in combating climate change through the generation of clean solar energy. This research aims to provide valuable insights into the implementation of solar-powered EV charging stations in Pakistan, addressing the country's energy requirements, promoting sustainable transportation, and contributing to the reduction of greenhouse gas emissions.

Singh et al. (2021) analyzed the design and performance of a solar-powered electric vehicle (EV) charging station in Indian cities. They found that an 8.1 kWp solar PV system with two days of battery autonomy had the lowest energy losses and could charge around 414 vehicles per year, reducing CO_2 emissions by approximately 7950 kg. Monocrystalline modules were found to have better energy generation and economic performance compared to polycrystalline modules [1]. Shariff et al. (2020) developed and tested a solar-powered level-2 electric vehicle (EV) charging station in India. Using software simulation and hardware testing, they found that the system's performance depended on solar radiation and the battery state of charge. The 6.4 kW solar PV charging station was installed at the Centre of Advanced Research in Electrified Transportation building at Aligarh Muslim University. The study focused on a 10 kWh lithium-ion battery pack on a sunny day at standard test conditions for the solar panel [2].

The study of solar-powered EV charging stations has paramount significance in light of rising environmental consciousness across the globe and the urgent demand for sustainable alternatives [3][4][5]. Understanding the technological complexities and financial viability of such systems becomes essential as the globe works to switch to cleaner, more energy-efficient forms of transportation.

In addition to the advantages for the environment, the investigation of solar-powered EV charging stations also addresses many other crucial issues. First off, reducing greenhouse gas emissions not only contributes to the achievement of global climate goals but also enhances air quality, especially in heavily populated urban areas [6][7]. By lessening the negative consequences of air pollution, this helps to improve outcomes for public health. Additionally, solar-powered EV charging stations can lessen the strain on national grids during moments of high electricity consumption. This is especially important for nations like Pakistan where there are frequent electricity shortages and integrating renewable energy sources can improve grid stability and energy security [8][9][10].

In addition, by supporting innovation in clean energy technology and the creation of jobs in the renewable energy sector, the incorporation of solar electricity into transportation infrastructure can boost regional economies [11][12]. Moreover, it lessens the country's dependency on imported fossil fuels, increasing energy independence and reducing the effects of fluctuating international oil prices. Finally, as electric vehicles become more and more popular around the world, it is important to comprehend the technical and financial aspects of solar-powered charging stations to ensure Pakistan stays competitive in the rapidly developing electric mobility market, which could have significant economic ramifications for the nation [13][14][15].

II. DESIGN

The following elements are essential for an EV battery to be charged in a reasonable amount of time at the charging station.

A. Solar panel array

To recharge the EV battery, a solar panel array, mounted on the solar tracker, is used based on the battery's size, the charging rate required, and the sunlight available. A solar PV panel is made up of silicon-based semiconducting materials that conduct electricity when exposed to light. The cells don't require direct sunlight to function, even on cloudy days. On the other hand, power generation rises with sun intensity. Solar panels take in photons, which subsequently begin an electric current. The energy generated when photons collide with a solar panel's surface allows for the release of electrons from their atomic orbits. The electric field generated by the solar cells subsequently attracts these liberated electrons into a directed current. This is known as the Photovoltaic Effect.

A solar tracker is a device that rotates reflecting surfaces or the solar panel's face to follow the sun as it crosses the sky. When solar trackers are used in conjunction with solar panels, the panels can track the sun's movement and generate more sustainable energy. The solar panels have solar tracking equipment attached to their racking, allowing them to follow the sun's path.

B. Solar charge controller

To regulate the electricity flow from the solar panel array to the battery storage system, a solar charge controller is used. A solar charge controller, which is connected between the solar panels and the battery, is a solar battery charger and controls how batteries are charged. It controls how much power the solar array's battery bank receives. It makes sure the batteries are charged properly, aren't overcharged during the day, and aren't drained at night by power running back to the solar panels.

C. Battery storage system

To store the excess electricity generated by solar panels to give the EV power even when the weather is cloudy, a battery storage system is used. PV systems utilize batteries for solar energy storage throughout the day, which they then release at night or when no other energy is present. This is referred to as the battery's cycle (charge and discharge period). For vehicles and other PV applications, deep-discharge lithium-ion batteries are frequently employed.

D. EV charger

To deliver electricity to the EV battery from the battery storage system, an EV charger is used. An EV charger offers several benefits compared to a 13A plug. Compared to a 13A plug point, EV chargers can charge EVs at faster rates (several times) depending on their rated capacity. It includes numerous built-in safety features that increase overall safety, such as OTP/RFID authorization systems, remote access, and control, smart charging, etc., which are not available on the 13A plug.

E. Inverter

To convert the solar panel's DC electricity into AC electricity, which can be used by the EV charger, an inverter is used. The PV system has a solar inverter attached, which is where solar energy is delivered and then converted to alternating current. The need for a separate EV charger, additional wiring, and electrical modifications are all removed by integrating an EV charger with a solar inverter that charges electricity from rooftop solar panels.

Table 1 shows the comparison between different battery technologies for EV applications

TABLE I: Comparison of different battery technologies for EV applications

Battery Technology	Advantages	Disadvantages
Lead-acid	Low-cost, widely available	Heavy, short lifespan, requires maintenance
Nickel-metal hydride	High energy density, long lifespan	Expensive, toxic materials
Lithium-ion	High energy density, long lifespan, low maintenance	Expensive, requires protective measures for safety

An estimate of various solar-powered EV charging station parts prices is shown in Table 2:

TABLE II: Cost comparison of different components for a solar-powered EV charging station

Component	Cost (in Pakistani Rupees)
Solar panel array	50,000-100,000
Solar charge controller	10,000-20,000
Battery storage system	30,000-50,000
EV charger	20,000-30,000
| Inverter	15,000-25,000
Total cost	**125,000-230,000**

Figure 1 shows the block diagram of the solar-powered EV charging station.

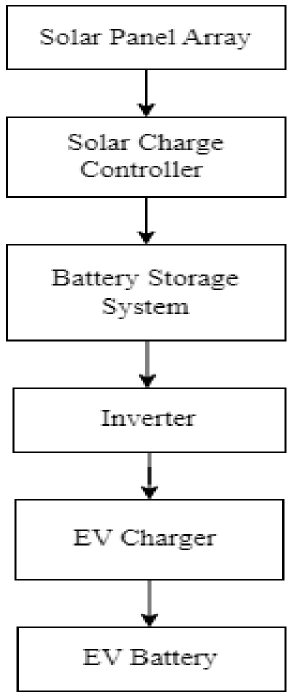

Fig. 1. Block diagram of a solar EV charging station

As shown, the solar panel array generates the electricity, then, is controlled by the solar charge controller, is stored in the battery storage system, then, is transformed into AC electricity by the inverter, and then, the EV charger transfers the electricity to the EV battery from the battery storage system

III. AC AND DC CHARGING

Due to the different parts and terminology used, charging for electric vehicles can frequently be perplexing. One such instance is the term "charger" being used to describe both the charging cables and connections as well as the specific hardware item (such as a wall box) that acts as an interface between the charging wires and the car. It's vital to remember that the actual power conversion occurs inside the car, not in these extraneous parts.

Onboard AC charging and off-board DC charging are the two basic forms of EV charging. Using an onboard charger (OBC) built into the EV, which transforms AC from the grid into DC power for the battery, is how onboard AC charging is done. Off-board DC charging requires using an external off-board charger to transform grid-supplied AC power into DC power for the battery. A wireless charging option is also available for some EVs, in which a transmitter outside the car transmits AC power to a receiver fitted on the EV.

AC charging involves the transfer of AC power from the grid to the EV through an AC outlet or charging station and is generally referred to as "slow charging" due to its power limitation (typically up to 22 kW) and the minimum necessary time to charge. On the other hand, DC charging involves the transfer of DC power directly to the EV, bypassing the need for onboard AC-DC conversion. DC charging is generally referred to as "fast charging" due to its higher power levels (typically above 22 kW) and shorter charging times. The various kinds of EV charging choices, their locations, and typical power ranges are listed in Table 1.

TABLE III: EV charging options and characteristics

Charger	Location	Typical power range
On-board charger (AC)	Integrated into the vehicle	3.7-11 kW, up to 22 kW
Wireless charger (AC)	Receiver integrated into the vehicle	3.2 kW – 11 kW
Off-board charger (DC)	Outside of the vehicle	Up to 350 kW

As there are fewer space, weight, and heat restrictions when charging occurs outside the vehicle, the range of DC charging power ratings for electric cars (EVs) is fairly wide. DC charging capacities can range from less than 11 kW to 400 kW. However, not all EVs can withstand high DC charging rates, and the majority of models that are now on the market are normally able to support at least 50 kW rates. The different ways that an EV can be charged are shown in Figure 1.

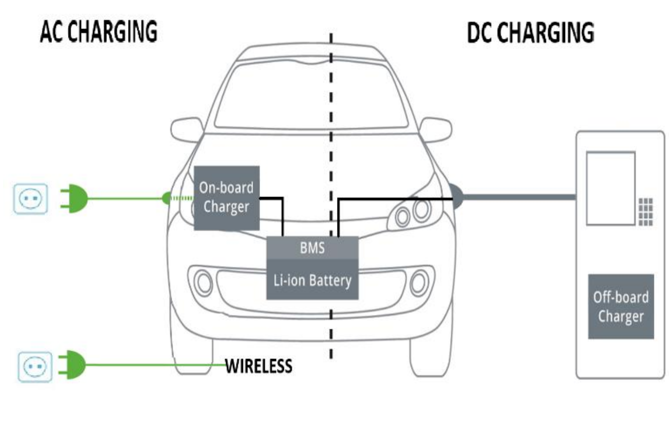

Fig. 2. A visual representation of On-board AC, Wireless AC, and Off-board DC charging methods

Due to its lower power output and lengthier charge times, AC charging is frequently referred to as "slow charging." There is no official definition for the terms "high power AC charging" or "rapid AC charging," which are commonly used to refer to the higher power ranges of AC charging (11 to 22 kW). The terms "fast" and "ultrafast" are both used to describe DC chargers with ratings of more than 22 kW and 50 kW, respectively. However, these terms lack a precise meaning. Dedicated charging stations with access to three-phase power connections frequently offer DC charging, which is typically more powerful than AC charging. Multiple ultrafast chargers with power ratings of more than 150 kW are frequently found at these stations. These facilities, however, need a specific high-voltage transformer from the grid.

The typical charging time for various EV battery capacities and AC charging speeds is depicted in Figure 2. As the battery size and AC charging rate rise, it is evident that the charging time lowers. It is crucial to remember that additional factors, such as the battery's age, ambient temperature, and level of charge at the beginning of the charging process, can also affect how long it takes to charge a battery.

TABLE IV: AC charging times for different EV battery sizes and charging rates

Battery Size (kWh)	3.7 kW Charger	7.4 kW Charger	11 kW Charger	22 kW Charger
24	8 hours	4 hours	2.7 hours	1.3 hours
30	10 hours	5 hours	3.3 hours	1.7 hours
40	13.3 hours	6.7 hours	4.4 hours	2.2 hours

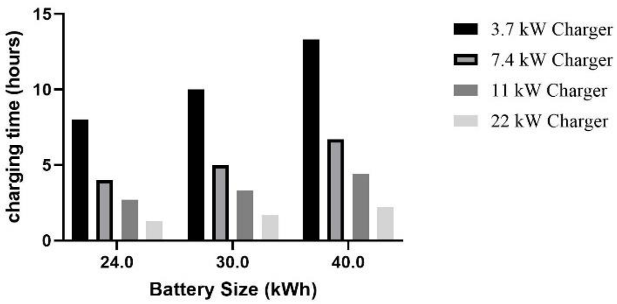

Fig. 3. Charging times for different EV battery sizes and AC charging rates

Due to the off-board charger's ability to perform the power conversion externally, DC charging offers substantially faster charging times than AC charging. The maximum rate for the majority of EV models ranges from 50 to 150 kW, and DC charging rates are often significantly greater than AC charging rates. This makes it possible for substantially quicker charging periods; the majority of EV batteries can charge from 0% to 80% in under 30 to 60 minutes. It is crucial to remember that charging an EV battery at its maximum DC rate is not necessarily the most effective method because the battery might not be able to completely utilize the high power input and may experience a shortened lifespan as a result.

TABLE V: DC charging times for different EV battery sizes and charging rates

Battery Size (kWh)	50 kW Charger	75 kW Charger	100 kW Charger	150 kW Charger
24	30 minutes	20 minutes	15 minutes	10 minutes
30	37.5 minutes	25 minutes	18.75 minutes	12.5 minutes
40	50 minutes	33.3 minutes	25 minutes	16.7 minutes

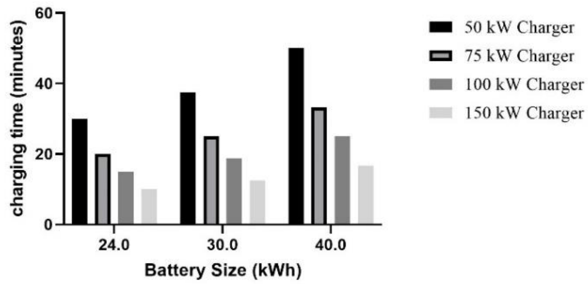

Fig. 4. Charging times for different EV battery sizes and DC charging rates

Some EV models also feature wireless charging as an alternative to AC and DC charging. To avoid the use of physical charging cords, wireless charging involves the transfer of energy from a charging pad or mat to a receiver on the EV. Although wireless charging often has lesser power transfer rates than AC or DC charging, some consumers may find it to be a convenient alternative due to the lack of a physical charging cord.

TABLE VI: Wireless charging times for different EV battery sizes and charging rates

Battery Size (kWh)	3.2 kW Charger	6.6 kW Charger	11 kW Charger
24	10 hours	5 hours	3.3 hours
30	12.5 hours	6.3 hours	4.1 hours
40	16.7 hours	8.3 hours	5.5 hours

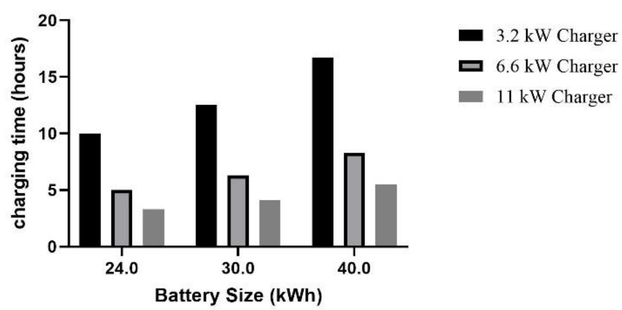

Fig. 5. Charging times for different EV battery sizes and wireless charging rates

Many variables, such as the battery size, charging rate, infrastructure type, and outlet or charging station being utilized, affect how long it takes an EV to charge. It is feasible to optimize the charging time for an EV and make sure it is prepared to go when needed by carefully taking into account these parameters.

IV. PERFORMANCE FACTORS FOR THE SOLAR SYSTEM AND BATTERY PACK IN THE EV CHARGING STATION

The following calculations are performed to establish the dimensions and technical requirements for the solar panel system, solar panel, and batteries required for a solar-powered electric vehicle (EV) charging station in the Pakistani market. We can calculate the quantity of solar energy required to meet daily energy needs, the number and size of solar panels required, and the quantity and operating voltage of the batteries using the MG ZS EV electric car model as an example. Based on these calculations, an effective solar-powered EV charging station suitable for the Pakistani market can be designed and built.

A. *Calculating the Size of the Solar System*

Equation (1) can be used to calculate the solar system's size.

$$\text{Solar system size (kW)} = \frac{\text{Daily output (kWh)}}{\text{Average sunshine (hours) in Pakistan}} \quad (1)$$

$$\text{Solar system size (kW)} = \frac{60 \text{ kWh}}{6 \text{ hours}} \quad (2)$$

$$\text{Solar system size (kW)} = 10 \text{ kW} \quad (3)$$

Equation (4) can be used to calculate the number of solar panels needed for a solar system with 400 W, 45 V, and 10 A.

$$\text{Number of panels} = \frac{(\text{Solar system size (kW)} \times 1000 \text{ W/kW})}{\text{Peak power (W)}} \quad (4)$$

$$\text{Number of panels} = \frac{(10 \text{ kW} \times 1000 \text{ W/kW})}{400 \text{ W}} \quad (5)$$

$$\text{Number of panels} = 25 \quad (6)$$

Equation (10) can be used to calculate the total solar panels' area.

$$\text{Area of solar panel} = \text{Length} \times \text{Width} \quad (7)$$

$$\text{Area of solar panel} = 2.4384 \times 1.2192 \text{ cm} \quad (8)$$

$$\text{Area of solar panel} = 2.97\ m^2 \quad (9)$$

Now,

$$\text{Total Area of solar panels} = \text{Number of panels} \times \text{Area of solar panel} \quad (10)$$

$$\text{Total Area of solar panels} = 25 \times 2.97 \quad (11)$$

$$\text{Total Area of solar panels} = 74.25\ m^2 \quad (12)$$

B. *Determining the Area of the Solar Panel System*

Equation (13) can be used to calculate the required MG ZS EV car area.

$$\text{Area of EV} = \text{Length} \times \text{Width} \quad (13)$$

$$\text{Area of EV} = 4.314 \text{ m} \times 1.809 \text{ m} \quad (14)$$

$$\text{Area of EV} = 7.804\ m^2 \quad (15)$$

Equation (16) can be used to calculate the required total plant area.

$$\text{Total plant area} = \text{Total area of solar panels} + \text{Area of EV} \quad (16)$$

$$\text{Total plant area} = 74.25\ m^2 + 7.804\ m^2 \quad (17)$$

$$\text{Total plant area} = 82.054\ m^2 \quad (18)$$

C. *Calculating the Number of Batteries Required*

Equation (19) can be used to calculate the required number of cells in the battery pack.

$$\text{Number of cells} = \frac{(\text{Total output power (kW)} \times 1000 \text{ W/kW})}{\text{Output power per cell (W)}} \quad (19)$$

$$\text{Number of cells} = \frac{(44.5\text{kW} \times 1000 \text{ W/kW})}{15 \text{ W}} \quad (20)$$

$$\text{Number of cells} = 2966.66 \text{ cells} \quad (21)$$

$$\text{Number of cells} = \sim 2967 \text{cells} \quad (22)$$

To calculate the ampere output of the battery pack, equation (23) can be used to calculate the battery pack's ampere output.

$$\text{Ampere output} = \frac{(\text{Total output power (kW)} * 1000 \text{ W/kW})}{\text{Voltage (V)}} \quad (23)$$

$$\text{Ampere output} = \frac{(44.5 \text{ kW} * 1000 \text{ W/kW})}{400 \text{ V}} \quad (24)$$

$$\text{Ampere output} = 111.25 \text{ A} \quad (25)$$

Equation (26) can be used to calculate the number of cells in parallel.

$$\text{Number of cells in parallel} = \frac{\text{Number of cells}}{(\text{Voltage/Normal cell voltage})} \quad (26)$$

$$\text{Number of cells in parallel} = \frac{2967 \text{ cells}}{(400 \text{ V} / 3.6 \text{ V})} \quad (27)$$

$$\text{Number of cells in parallel} = \frac{2967 \text{ cells}}{111.11} \quad (28)$$

$$\text{Number of cells in parallel} = 26.70 \text{ cells} \quad (29)$$

$$\text{Number of cells in parallel} = \sim 27 \text{ cells} \quad (30)$$

Now, the equation (31) can be used to calculate the number of cells in series.

$$\text{Number of cells in series} = \frac{2967}{27} \quad (31)$$

$$\text{Number of cells in series} = 109.88 \text{ cells} \quad (32)$$

$$\text{Number of cells in series} = \sim 110 \text{ cells} \quad (33)$$

Thus, to achieve the required battery capacity, 110 cells would be connected in series and 27 cells would be connected in parallel.

D. Estimating the Safe Operating Voltage Range for the Batteries

Assuming that the lithium-ion battery has a normal cell voltage of 3.6 V and an end-of-discharge voltage of 2.8 V to 3.0 V. Typically, the maximum charge voltage is 4.2 V. For the battery pack, the maximum charge voltage would be [110 cells x 4.2 V = 373.8 V]. Exceeding this limit can damage the batteries and raise the temperature. When the voltage reaches $[89 \text{ cells} \times 2.8 \text{ V} = 249.2 \text{ V}]$, the battery will be in a discharged state.

These calculations showed that a solar system with a size of 10 kW, using 25 solar panels and covering an area of approximately 7.804 m^2, is needed to power an MG ZS EV electric car in Pakistan. The battery pack would need to have 2967 cells, with 110 cells connected in series and 27 cells connected in parallel to achieve the desired capacity.

V. SENSITIVITY ANALYSIS

In this section, sensitivity analysis was done to determine how the design of an EV charging station powered by solar energy is affected by modifications in some different variables. The equations and presumptions discussed in the previous section were used to compute the estimated charging time.

Table 1 displays the results of the sensitivity analysis for the capacity and size of the EV battery and solar panel array. All other factors were held constant while varying the EV battery's capacity from 44.5 to 60 kWh and the solar panel array's size from 4 to 10 kW.

TABLE VII: Sensitivity analysis of solar panel array size and EV battery capacity

Solar Panel Array Size (kW)	EV Battery Capacity (kWh)	Estimated Charging Time (hours)
4	44.5	9.89
6	44.5	6.59
8	44.5	4.89
10	44.5	3.89
4	60	13.19
6	60	8.79
8	60	6.39
10	60	4.79

Figure 5 shows the relationship between the solar panel array size and the estimated charging time. The projected charging time gets shorter as the solar panel array gets bigger. This is so that an EV battery may be charged more quickly thanks to a larger solar panel array's ability to produce more electricity.

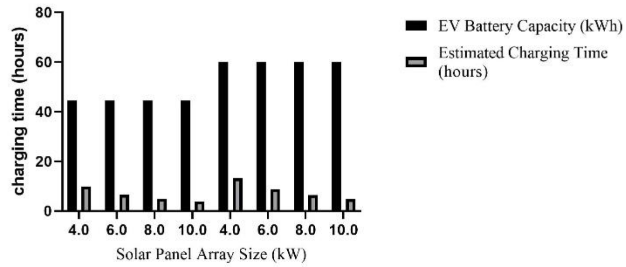

Fig. 6. Solar panel array size vs estimated charging time

The sensitivity analysis for solar panel efficiency and EV battery capacity is presented in Table 7. The solar panel array efficiency was modified from 15% to 20% while the EV battery capacity was varied from 44.5 kWh to 60 kWh while all other factors were held constant.

TABLE VIII: Sensitivity analysis of solar panel efficiency and EV battery capacity

Solar Panel Efficiency (%)	EV Battery Capacity (kWh)	Estimated Charging Time (hours)
15	44.5	11.69
20	44.5	9.89
25	44.5	8.69
15	60	16.09
20	60	13.19
25	60	11.49

The correlation between the anticipated charging time and solar panel efficiency is depicted in Figure 6. The anticipated charging time decreases as solar panel efficiency increases. This is done so that an EV battery can be charged more quickly using the extra energy that a solar panel with higher efficiency can produce per unit of surface area.

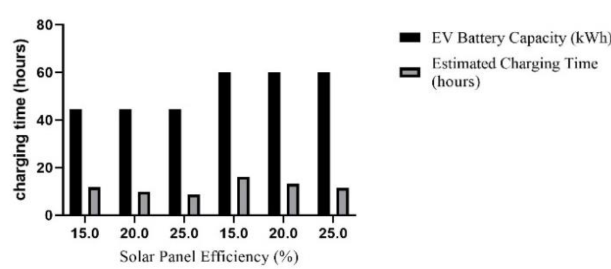

Fig. 7. Solar panel efficiency vs estimated charging time

The sensitivity analysis for solar panel array size and efficiency is displayed in Table 8. By keeping the remaining factors constant, the size of the solar panel array was increased from 4 kW to 10 kW, and the efficiency was modified from 15% to 25%.

TABLE IX: Sensitivity analysis of solar panel array size and solar panel efficiency

Solar Panel Array Size (kW)	Solar Panel Efficiency (%)	Estimated Charging Time (hours)
4	15	11.69
6	15	8.29
8	15	6.59
10	15	5.49
4	20	9.89
6	20	7.19
8	20	5.69
10	20	4.79
4	25	8.69
6	25	6.39
8	25	5.19
10	25	4.39

Figure 7 shows the relationship between the expected charging time and the solar panel array size. The projected charging time gets shorter as the solar panel array gets bigger. This is so that an EV battery may be charged more quickly owing to a larger solar panel array's ability to produce more electricity.

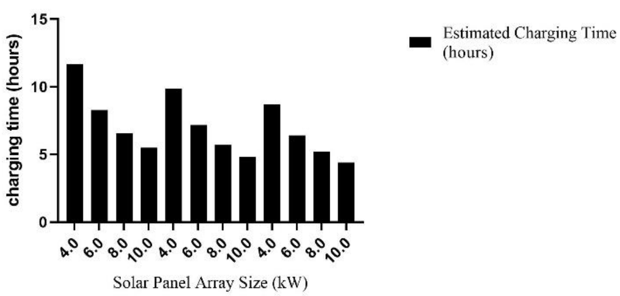

Fig. 8. Solar panel array size vs estimated charging time

The correlation between the anticipated charging time and solar panel efficiency is depicted in Figure 8. The anticipated charging time decreases as solar panel efficiency increases. This is because a solar panel with higher efficiency might generate more energy per unit of surface area, which can be used to fast charge an EV battery.

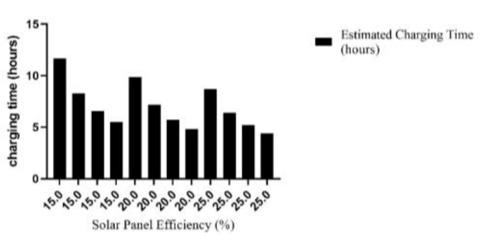

Fig. 9. Solar panel efficiency vs estimated charging time

Therefore, when building the charging stations, the solar panel array and solar panel efficiency must be taken into account. Faster EV charging is possible with a larger solar panel array. It takes longer to charge an EV if its battery is larger, whereas the reverse is true if its battery is smaller. The sensitivity analysis's findings indicate that to reduce the amount of time an EV must charge, these factors must be optimized.

VI. . LOSSES IN SOLAR POWER GENERATION: FACTORS AND MITIGATION STRATEGIES

The following are some major factors that affect the system's overall efficiency.

A. *During Photovoltaic Conversion (Solar Plates)*

Solar panels convert the sun's radiation in the form of light into usable electricity. All the sunrays falling on the solar panels aren't converted into DC energy. Some of its amounts get dissipated as heat into the environment. For example, till mid-day, a solar panel of 1 m2 receives sunlight energy of 1000 watts, but the efficiency of the solar panel is 15% and converts 150 watts of energy into DC energy. Thus, the remaining 850 watts are lost in the form of heat. This loss during the conversion affects the ratio of total usable energy. The dirt on the solar plates acts as an obstacle to the dissipation of solar light, which causes a lower ratio of energy to be converted. Unclean solar plates face an efficiency loss over time of up to 0.25%. The light-induced degradation causes efficiency loss in the solar panel system. When the solar panel systems are operated initially, the boron coating over the solar panels oxidizes and partially clouds the panels, which causes a lowering of efficiency by over 1 to 3 percent.

B. *During the Chemical Conversion (Batteries)*

In the solar plates, the electricity is produced in the form of DC and travels in two directions; one for consumption and the other to be stored in the batteries. During the daytime, there is no dependence on the batteries—but during the night or in a cloudy climate, when there is merely solar energy production, the energy is dependent on the solar battery efficiency. When the energy is not being used from the solar panels to charge the vehicle, then that energy is stored in the solar batteries in the form of chemical energy, which can be used later to charge the vehicle when there is an insufficient number of sunrays or at night. If the solar battery has lost efficiency due to orientation, time, wearing out, etc., then the overall energy efficiency of the solar panel system will be affected. For example, if a solar battery has an efficiency of 88%, then it will only output 82% of the chemical energy stored in it into DC energy. There can be various reasons that can affect the working efficiency of the solar batteries, such as if the solar inverter is throwing amps that are too high for the battery, it would charge the battery quickly, satisfying the user or charge controller to turn the charging off, but ultimately, there would not be enough power in the battery to back up. Differences between the voltages of the solar batteries can cause the same early charging discrepancy, which will cause the battery to lose efficiency. The solar batteries are affected by high temperatures—keeping them at a temperature above 95°F will cause internal discharge, which will result in battery drain.

C. During DC to AC Conversion (Solar Inverters)

A solar inverter's primary purpose is to change the direct current that solar panels produce into an alternating current. During this conversion, it is possible to face conversion losses. The efficiency ratio of solar inverters ranges from 95% to 99%, which is affected by some compatibility and load factors. If the input power or any parameters are not set, it can drop. There are 30% losses in a solar inverter with a 95% efficiency rating since the inverter can only operate at 95% efficiency if the load, input power, and all other parameters are precisely matched. Installing high-efficiency-based MPPT modules on the solar inverters will help in the proper conversion of DC energy to AC energy.

D. Transfer Losses (Wires)

Transfer losses, which are the losses from the power transportation from the solar panels to the consumption, occur through not only the cables used for transmitting current but also through inverters or switches. This can be overcome by the use of inverters, high-efficiency rated inverters low-resistance wires, and by reducing the length of wires.

E. Environmental Factors

Solar panels are greatly affected by different climatic conditions. In high-humidity conditions, the solar panels' performance deteriorates due to the absorption of sunlight by the water vapor in the air. In colder conditions, the solar panels' performance deteriorates due to the slow speed of electron flow.

F. Maintenance and Age

Proper maintenance, such as cleaning the solar panels to remove the debris that obstructs the sunlight and checking that all components are working properly, is required for a solar system to function properly. Solar panels also lose efficiency by about 0.5% annually as the material, which is used in their production, deteriorates due to sunlight exposure.

G. Cloud Cover and Shading

When the sun is covered by clouds or if the solar panels are shaded by nearby objects, their efficiency will be decreased. To maximize their efficiency, the solar panels should have a high-efficiency rating, be facing squarely toward the sun, and be placed at a location with no shade.

VII. OVERALL SYSTEM EFFICIENCY

The proportion of energy produced by a solar panel system to the energy consumed by the end user determines the system's overall efficiency. Numerous variables, such as PV conversion losses, transfer losses, and ambient variables, might affect its efficiency. The systems with high photovoltaic conversion losses may be less effective than systems with low conversion losses. Measures must be taken to increase efficiency to reduce any potential losses.

TABLE X: Overall system efficiency

Photovoltaic Conversion Losses (%)	**Chemical Conversion Losses (%)**	**DC to AC Conversion Losses (%)**	**Transfer Losses (%)**	**Overall System Efficiency (%)**
85	12	30	10	43
82	10	3	20	45
79	8	1	30	47

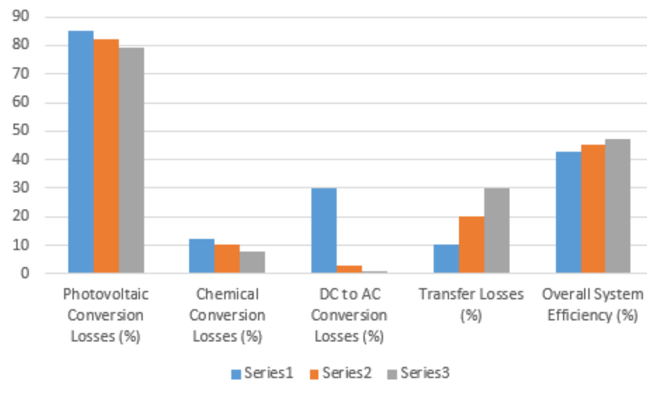

Fig. 10. Overall system efficiency

As shown, the overall system efficiency of a solar panel system can range from 43% to 47%. Based on specific conditions of the solar panel system, these figures might change. The efficiency can be calculated by each factor number. The losses that occur during the various conversion stages, as well as environmental conditions, maintenance, age, cloud cover, and shading, all have an impact on the total system efficiency. To overcome these factors, mitigation strategies should be applied.

VIII. STRATEGIES FOR BOOSTING SOLAR ENERGY OUTPUT

There are several ways to improve solar energy collection and raise solar panel systems' overall performance. Some of these methods include:

A. Selecting an Optimal Location

The location of the solar panel system has a big impact on how much solar energy is gathered. Where there is little to no shade and direct sunlight, the best place to install solar panels is. When selecting a location, latitude, direction, slope, as well as the locality and weather patterns, should all be taken into consideration.

B. Optimizing Panel Orientation and Tilt

The solar panels' efficiency also depends on their orientation and angle. To capture the most sunlight, solar panels work best when they are tilted toward the sun. Determine the proper orientation and tilt by considering the latitude, climate, and season of the area. In addition, the solar panels must be oriented with the latitude of the region in mind, facing south in the northern hemisphere and north in the southern.

C. Cleaning and Maintaining the Solar Panels

Daily upkeep, such as looking for broken parts and clearing off the dirt, can help solar panels work more efficiently.

D. Using High-Efficiency Solar Panels

The usage of solar panels with greater efficiency ratings can boost their performance and result in long-term cost savings.

E. Using Solar Tracking Systems

Solar trackers can help increase solar panel efficiency by changing the orientation and tilt of solar panels, which increases the amount of sunshine the solar panels receive.

F. Using Solar Boosters and Concentrators

Solar boosters are typically used to increase the amount of sunshine that the solar panels get while the sun is lower in the sky. Solar concentrators direct sunlight onto solar panels, increasing the amount of energy generated.

G. Increasing Solar Panel Efficiency

Using solar panels with a higher efficiency rating and technologies like thin-film solar panels or multi-junction solar cells can help increase the efficiency of a solar panel system.

H. Reducing Losses in the Conversion Stages

Utilizing batteries and solar inverters, as well as carrying out regular maintenance and cleaning on the components, can assist in decreasing losses and boost the effectiveness of the solar panel system.

I. Using Energy Storage Systems

By minimizing the quantity of energy lost as a result of unwanted surplus output, energy storage devices can aid in improving the overall efficiency of a solar panel system.

J. Using Reflective Surfaces

The use of reflective surfaces, such as mirrors or reflective paint, can boost the amount of energy generated by the solar panel system by up to 20%.

IX. CONCLUSION

Electrified transportation, particularly electric vehicles (EVs), offers a clean, efficient, and noise-free alternative to traditional internal combustion engine vehicles. The integration of renewable energy sources, such as solar power, into the charging infrastructure of EVs further enhances their sustainability. Factors such as panel orientation, tilt angles, and the use of high-efficiency solar panels play a crucial role in maximizing the efficiency of solar-powered EV charging stations. By considering these design aspects, Pakistan can effectively transition towards a future driven by EVs. However, further research is necessary to fully assess the viability and success of solar-powered EV charging stations in the Pakistani market. Future studies may include in-depth case studies of successful initiatives implemented in other countries, providing valuable insights into the local context. In conclusion, this research highlights the potential of solar-powered EV charging stations as a viable and sustainable solution for the Pakistani market. The findings of this study underscore the need for continued research and development in this field, ultimately paving the way for the successful implementation of solar-powered EV charging stations in Pakistan and fostering the widespread adoption of EVs as a sustainable transportation option.

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