

Article

A Sustainable Solution for Urban Transport Using Photovoltaic Electric Vehicle Charging Stations: A Case Study of the City of Hail in Saudi Arabia

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Abstract: As the global shift toward sustainable transportation gains momentum, the integration of electric vehicles (EVs) becomes imperative, necessitating a robust and environmentally friendly charging infrastructure. Leveraging the abundant solar potential in the region, this study examines the technical, economic, and environmental feasibility of deploying photovoltaic electric vehicle charging stations (PV-EVCSs) in Hail City, Saudi Arabia, as a case study. This study examines factors such as the energy demand, grid integration, and user accessibility, aiming to address the challenges and opportunities presented by the urban fabric. The proposed solar charging station network seeks to catalyze a paradigm shift toward a cleaner and more sustainable transportation ecosystem, embodying a forward-thinking approach to meeting the evolving needs of urban mobility in the 21st century. The analysis encompasses many scenarios, encompassing a range of car battery sizes, charger powers, and car slots per station. Zone 4 is identified as the most crucial area, where seven charging stations are needed to fulfill the expected demand in the absence of any private charging alternatives. The economic evaluation of the 1047.35 kWp PV system reveals an estimated conventional payback time of 11.69 years, accompanied by a return on assets of 10.17%. The system generates accumulated cash flows amounting to SR 7,169,294.62 over 30 years, while the estimated operational and maintenance expenses are predicted to be SR 50,000 per year. The overall investment cost for the solar PV and EV charging stations is SR 4,487,982. This cost is offset by the yearly electricity savings from solar and grid sources, which can reach up to SR 396,465.26 by year 30. This work presents a detailed plan for the future of sustainable transport. It combines technical, environmental, and economic aspects to promote a cleaner and more sustainable urban mobility system.



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1. Introduction

As the global pursuit of sustainable energy solutions intensifies, the integration of electric vehicles (EVs) into urban areas has become a pivotal aspect of modern transportation planning for a sustainable future. Demand for a reliable and widespread charging infrastructure is rising along with the popularity of EVs. This paper focuses on Hail City, situated in the heart of the Kingdom of Saudi Arabia (KSA), as a case study to explore the design and implementation of a solar charging station network for EVs. This study aims to address the challenges and opportunities presented by the urban landscape and develop a comprehensive blueprint that aligns with the Kingdom's vision for a greener and more sustainable transportation sector. The geographical and climatic characteristics of Hail City provide a distinctive context for the implementation of solar charging stations.

With abundant sunlight throughout the year, leveraging solar energy not only contributes to the reduction of greenhouse gas (GHG) emissions but also aligns with Saudi Arabia's vast renewable energy (RE) potential. This research endeavors to explore the technical, economic, and environmental feasibility of integrating solar charging infrastructure into the existing urban framework of Hail City, considering factors such as the energy demand, grid integration, and user accessibility. Furthermore, this study delves into the potential economic and societal impacts of adopting photovoltaic electric vehicle charging stations (PV-EVCSs). It seeks to assess the long-term sustainability and scalability of the proposed model, keeping in mind the evolving landscape of urban mobility and the Kingdom's ambitious Vision 2030 goals. By combining the advantages of electric mobility and solar energy, the solar charging station network aims to serve as a pioneering model for other urban centers in the KSA and beyond, fostering a paradigm shift toward a cleaner and more sustainable transportation ecosystem.

With a land area of almost 2.15 million km², the KSA is the biggest nation in the Middle East and the 13th largest in the globe. The KSA now has a population of approximately 37.5 million, having grown significantly over time [1]. The KSA is well known for having large reserves of fossil fuels, especially oil [2]. The KSA is ideally suited for photovoltaic (PV) technology due to its abundant solar resources [3]. The KSA stands to gain a great deal by utilizing its solar potential, including lower GHG emissions, better air quality, increased energy security, and energy diversification. Intending to produce 50% of the nation's electricity from renewable sources by 2030, the government has launched an ambitious RE plan [4–6]. In addition to making large investments in wind and solar power plants, this plan calls for building a strong infrastructure to enable the integration of RE sources [6]. A regulation controlling the usage of EVs in the KSA was published in 2018 by the Saudi Standards, Metrology, and Quality Organization [7]. In 2021, the country launched its green initiative to mitigate the effects of climate change. Raising the percentage of EVs to 30% of all cars in Riyadh is one of the initiatives [8].

The end users of the final conventional energy source consumption in the KSA, including companies and households, account for the majority. These users utilize these sources to power industries, run lights, appliances, and transport, as well as to cool and heat buildings. Energy usage is significantly influenced by transportation. The transport sector recorded 31–33% of the overall energy demand from 2012 to 2019. Statistics also show that the percentage decreased to 27.65% of the total conventional energy sources consumption in the year 2021, see Table 1. This decrease may be due to the increase in the price of fuel. However, efforts have been made to address environmental concerns. In addition, the fuel efficiency of new small vehicles increased by 10% in 2016 as a result of the introduction of fuel economy performance requirements. Additionally, labels for fuel efficiency have been introduced, with particular labels for EVs [9].

Table 1. Total final conventional energy sources consumption, Saudi Arabia, 2021 [10].

	Industry	Transport	Residential	Commercial and Public Services	Agriculture/Forestry	Non-Energy Use	Non-Specified
Energy consumption (TJ)	1,510,594	1,791,125	591,908	431,690	17,673	2,134,245	1679
Percentage (%)	23.32	27.65	9.14	6.66	0.27	32.94	0.03

Like many other nations, the KSA's current power infrastructure is ill-suited to supporting the mass deployment of EVs. This research focuses on Hail City as a case study to demonstrate the need for electric vehicle charging stations (EVCSs) to take advantage of PV. Hail, a city renowned for both its quick industrialization and its historical significance, is having to deal with more and more urbanization-related issues, such as an increase in traffic and the ensuing effects on the environment. In light of this, it is imperative to comprehend Hail's EV adoption and viability for the city's sustainable future. This study on the potential of EVs in Hail has the potential to provide insightful

information that can guide municipal legislation, urban planning, and infrastructure development as efforts throughout the world to combat climate change and switch to greener energy sources increase.

2. Literature Review

The literature discusses the difficulties of and impediments to the mainstream adoption of EVs. As per Alkawsi et al. [11], solar energy is considered a dependable alternative to conventional energy sources due to its economic and environmental advantages. Therefore, it can be inferred that solar energy sources are the most appropriate for the EV charging infrastructure. EV consumers' attitudes and views have been the subject of numerous research studies. To offer insight into the potential adoption and impacts of EVs in Hail City, KSA, as well as the move away from conventional cars, Al-fouzan and Almasri [12] conducted a survey. With 37.9% of participants stating they would be pleased to switch to an EV and 78.6% of participants knowing where EV charging stations are, the results show a clear preference for EVs. The findings indicate growing interest in EVs and highlight the need to construct strategic infrastructure to manage the anticipated increase in EV adoption. An exploratory study of German users' acceptance of battery switching and solar charging stations was carried out by Schelte et al. [13]. The authors claim that between 50% and 80% of potential sharing system users wish to accept battery swapping and solar charging stations. The majority of responders (71–77%) claim that battery swapping and solar charging facilities are simple to operate. The authors claim that a discount of between 10% and 20% off the subsequent sharing trip would be a sufficient inducement for the majority of respondents. While more men than women plan to use battery swapping stations, more female respondents want to use solar charging stations. Pevec et al. [14] were able to measure range anxiety by polling both EV owners and non-owners and finding a correlation between range anxiety and the best distance between adjacent charging stations. The majority of EV owners are based in the United States (US) or the United Kingdom, whereas the majority of poll respondents who do not own an EV are from Croatia. According to the scientists, both groups' average optimal distance between adjacent charging stations was found to be roughly 7 km. Almutairi's survey [15] was used to investigate the EV potential of participants from five distinct regions of the KSA. The respondents' age, gender, place of residence, kind of vehicle they drove, chance of buying an EV, average travel distance, point of departure and arrival, and preferred auto-charging facility were all questioned in the survey. More than 80% of the participants were either definitely inclined or probably inclined to purchase an EV within the next five years after being given three options, according to the data analysis. Because He and Hu [16] were worried about the charging behavior when EVs were being utilized, they investigated the battery EV charging method while taking into account the tension between charging times and range anxiety. The authors proposed a mathematical model that accounts for both the infrastructure for charging and the driving experience to measure range anxiety. The results show that the optimal absolute mileage increases with the battery EV cruising range and driver tolerance for range anxiety. It is interesting to note that the optimal relative mileage increases with drivers' tolerance for range anxiety but decreases with BEV cruising range.

In the European Union, 61% of EV owners charge their vehicles at home, while 15% charge them at work. Bailey et al. [17] in Canada and Almutairi [15] in the KSA reported that more than 60% of respondents chose the home as the ideal location for EV charging. According to research by Todts and Mathieu [18], about 25% of EVs were charged at public charging stations. It is projected that the percentage of home charging will decline from 61% in 2020 to 45% in 2030. Even though EVs appear to be less expensive than traditional cars, adoption barriers still exist. To obtain a further understanding of the experiences of Norwegian homeowners after EVs were smartly charged, Henriksen et al. [19] carried out a qualitative investigation. The results suggest that people's decisions to use smart charging could have just as much weight as their financial arguments. Added physical comfort, economical and practical benefits, user happiness, and fire safety are some of

these factors. Additionally, the results showed that future opportunities for flexibility and grid optimization would depend on how various reasons for deploying smart home technology are expressed. Van Heuveln et al. [20] looked at the attitudes of Dutch EV drivers toward vehicle-to-grid and offered information on the variables influencing their adoption of the technology. The most crucial elements in relation to promoting user acceptance, according to the authors, were compensation, open system operations, and dependable user control. Numerous incentives, such as tax breaks, the ability to install wall chargers in customers' homes, unrestricted access to highways, additional co-financing for EV purchases, and reimbursement of a portion of the purchase price, were listed by Sendek-Matysiak and Łosiewicz [21] as ways to encourage EV adoption. Xu et al. [22] investigated the effects of electrified passenger cars in Regina, Canada. According to a recent survey, 25% of Regina residents stated they would install solar panels on their roofs even if they were not compensated for doing so, and the majority of respondents support wind farms. To better understand the acceptance mechanisms and increase user adoption, Wang et al. [23] assessed the customer acceptability of electric vehicle charging stations (EVCSs) in Hangzhou, China. Evaluations of the factors influencing acceptance and the variations in EVCS acceptance across social groups were conducted. According to the findings, 81.2% of the participants were open to taking part in EVCS.

A statistical examination of the impact of EV charging on the KSA's electrical grid was carried out by Almohaimeed [24]. The data indicate that the late evening and early morning are when the EV peak loads occur. Interestingly, the study shows that the peak EV periods line up with the off-peak hours on the daily demand curve. So, a large EV population can help the electric grid become more flexible and efficient. Moreover, the cumulative EV load of a large car population follows a smooth pattern and does not affect the nation's electric system. The results of Sheldon and Dua [25] are in line with this. Most participants reported making one or two weekly trips to the petrol station, and most respondents (more than 70%) indicated they engaged in between 10 and 60 km of daily travel. Elshurafa and Peerbocus [26] computed the net carbon emissions associated with the introduction of EVs in KSA by accounting for the energy mix. The Kingdom typically consumes a large amount of RE. Policies that support the deployment of EVs and RE sources concurrently may yield greater social and economic advantages. In contrast, the worst-case scenario sees a net increase in emissions. Additionally, it was demonstrated that other parameters, like the amount of time EVs, are charged did not significantly affect the reduction of emissions. Time-of-use pricing is not a practical way to promote a decrease in emissions, even though it can still be used to shift charging to off-peak hours and lessen part of the burden on the power system. A framework for home smart EV charger modeling and control was developed by Blonsky et al. [27]. The findings indicate that the recommended controller reduces the peak demand associated with EV charging and peak-period energy consumption. The authors noted that estimating stochastic variables, such as occupancy behavior and other variables influencing EV charging and other home load controllers, may be difficult in practical applications.

The development of infrastructure and urban planning are key factors that influence how feasible it is to integrate EVs. The most recent advancements in organizing, creating, and managing the CS for the utilization of EVs were examined by Mishra et al. [28]. They talked about how to generate the required energy using RE resources. Further study is required; however, the development of EVs and the associated charging infrastructure can reduce hazardous emissions. The lack of appropriate batteries that can store enough energy for a prolonged period and distance led them to the conclusion that the acceptance of EVs is a result of this. Cherry [29] stated that the great bulk of the infrastructure used to charge electric light-duty vehicles (ELDV) is made up of private chargers. Even though China only accounted for 47% of the world's ELDV inventory in 2019, it was home to 80% of the fast chargers that were available worldwide. Moreover, 12% of light-duty vehicle chargers worldwide are public chargers, with slow chargers making up the bulk. The year 2019 saw a 60% increase in the number of public chargers worldwide, both fast and slow,

surpassing the expansion of the ELDV stock. Over the past 10 years, solar PV systems have seen a notable increase in popularity as a distributed generation technology. According to Allouhi et al. [30], the total installed PV capacity worldwide grew from 483.1 GW in 2018 to 580.2 GW in 2019. Two major elements are responsible for this surge: the continuous improvement in PV system efficiency and the significant decrease in their cost over time. Over the past seven years, utility-scale solar projects have reached unprecedented levels of affordability for power generation, while the cost of residential and commercial solar PV systems has more than halved, as reported by Fu et al. [31]. As a result, solar energy has become a viable and affordable alternative, in addition to a clean electricity source. Nevertheless, because of daily and seasonal oscillations, solar power generation is not constant, which calls for the employment of energy storage systems. To match wholesale electricity rates, distribution system operators across the globe are also anticipated to lower the solar energy feed-in tariffs in the upcoming years. This change may have a major effect on the economics of integrating solar power into the grid and encourage solar energy self-consumption for EV charging and residential loads. According to Bauer et al. [32], the unrealized potential of the solar output on parking lots and workplace rooftops highlights the promising role of solar PV in EV charging.

There are two main benefits of charging EVs from solar PV systems: cost-effectiveness and sustainability. When compared to traditional techniques, PV-EVCSs exhibit higher energy efficiency, fewer net emissions, and a smaller environmental effect, as reported by Rangaraju et al. [33] and Messagie et al. [34]. Furthermore, in many parts of the world, solar PV electricity is already less expensive than traditional electricity due to the decreasing costs of PV systems. The total cost of ownership of an EV is already less than that of a vehicle with a comparable internal combustion engine in some auto categories [34]. Dörre et al. [35] investigated the feasibility of PV integration from an economic standpoint and looked into how the demand for EV charging may be distributed among different places (WIRO GmbH) in Germany according to socioeconomic factors. The findings demonstrate that PV systems can be integrated with infrastructure for charging and generating revenue. Specifically, how much more this extra value is will depend on the cost of electricity. According to the findings, PV integration makes financial sense when the cost of purchasing electricity is more than EUR 0.15 per kWh. The rising purchase price of power causes the added value to increase linearly. Daytime and slow charging are advantageous since they boost self-consumption and make photovoltaic systems financially feasible. For efficient PV integration, fast-charging infrastructure and PV storage systems should be paired. With or without the assistance of a fuel cell and electrolyzer system, Enescu et al. [36] provided a comprehensive design for an EVCS that is solar-based. According to the authors, the power-following strategy-based EVCS design's battery capacity was roughly 20 times lower than the design produced by the reference. Furthermore, the power-following strategy-based EVCS design was nearly half as expensive as the reference design. Costa and Cobas [37] conducted a case study on the installation of PV-powered charging stations alongside a major Brazilian highway. Along with offering information on electricity use, GHG emissions, and financial analysis, the authors also supplied a list of suitable places for the installation of the charging stations. The findings indicated that the expenses might be 72% less than what it currently costs to refuel conventional cars.

To meet the electrical load demand of a small shopping complex incorporating an EV charging station situated on an Indian university campus, Singh et al. [38] proposed a grid-connected solar–wind hybrid system. The component's size is chosen to minimize the levelized cost of electricity (LCOE). A total of 36 kW of solar and 20 kW of wind power, together with 10 kW of grid sales and buy, make up the ideal arrangement. The findings show that the renewable fraction is 0.87 and the LCOE is measured at USD 0.038 per kWh. A grid-connected PV-based microgrid for EV charging stations in Visakhapatnam City, India, was suggested by Chowdary and Rao [39]. The authors stated that the PV-powered charging stations and the scaled session determine the peak capacity required on the part of the solar power plant. The overall energy production varied from 946,235 to 1,734,764 kWh

annually, depending on the conditions. Approximately 97% of the power that was observed came from solar sources. On a highway in southern Tamil Nadu, India, Nishanthi et al. [40] looked into the techno-economic and environmental aspects of on-grid hybrid solar wind car charging stations. Throughout the day, the gadget may charge 17 EVs as planned. With a 50% reduction in emissions, the authors reported an LCOE of USD 0.072 per kWh and a net current cost of USD 303,291.26. Ye et al. [41] examined the technological and financial viability of PV-EVCSs in Shenzhen, China. Comparing the PV-powered EV to a typical gasoline-powered car, the former has a pollution reduction potential of about 100%. The LCOE rises from USD 0.027/kWh to USD 0.097/kWh with a loan rate increase from 0% to 6%. Hoth et al. [42] examined the solar energy potential of parking places for solar automobiles in Berlin, Germany. According to the findings, reducing grid charging might result in a median annual cost savings of EUR 164. The environmental advantages of solar car charging, however, were discovered to be inferior to those of conventional grid-connected photovoltaic systems. The study's conclusions suggest that solar-powered automobiles will not be able to overcome urban EVs' energy source issues. The current state of knowledge and the main forces behind initiatives to increase the adoption of PV-powered EVCS were compiled by Almasri et al. [43]. The results show that theoretical research using MATLAB (R2024a) was the most common use case, alongside parking lot shading projects. The energy consumption ranged from 0.139 to 0.295 kWh/km, according to the authors, and the LCOE for an on-grid system ranged from USD 0.0032 to USD 0.5645 per kWh. For this application, the payback time (PBT) is appropriate, which varies between one and fifteen years for most cases.

Based on previous studies, it is not clear that there is a case study of these techniques in hot and desert areas, although there are highlights of global trends in EV charging infrastructure, the integration of solar energy in transportation, challenges and opportunities in urban EV charging, relevant case studies, user behavior considerations, and the environmental and economic impacts of PV-EVCSs. The current study aims to build upon existing knowledge, providing a localized perspective on the potential solar power charging stations for EVs in urban areas. This comprehensive review serves as a foundation for the proposed research, informing the design and implementation of a solar charging station network in Hail City, KSA.

3. Methodology

The methodology for this study project is structured to systematically address the difficulties of creating an SCSN for EVs in the KSA's urban areas, with a focus on Hail City. To ensure a solid foundation for the latter stages of this study, the methodology begins with a thorough data-gathering phase from a range of sources, such as meteorological, transportation, infrastructure, and social data. This study will then include determining the number of stations needed, technical, economic, and environmental analysis, and finally, recommendations and conclusions.

Hail City (27°31' N, 41°41' E) is the capital of the Hail Region. Hail City's agricultural economy, along with its historical and ecological significance, establishes its character and relevance in the region [44]. The phases of urban development in Hail City have changed significantly over time. These patterns can be seen in the expansion of community services, population growth, and infrastructure development. This growth has made it necessary to expand infrastructure and services to meet the evolving demands of the city and its residents.

3.1. Data Collection

3.1.1. Climatic Data

In cooperation with King Abdullah City for Atomic and Renewable Energy, Hail University constructed a climate monitoring station on its roof, from which the set of meteorological data spanning the years 2018 through 2021 was collected. The monthly averaged statistics for the relative humidity, wind speed, and air temperature are comprehensively

visualized in Figure 1. Throughout the year, the average monthly temperature ranges from 16 to 35 °C. The hot time is from May to October, and August is the warmest month, although January is the coldest. The relative humidity is lowest in July and highest in January and December. It also appears from the figure that the average wind speed is approximately constant from 2 to 3 m/s throughout the year. The purpose of presenting these statistics is merely to create a rough forecast. As for the data used for calculations, we relied on the data available in the programs.

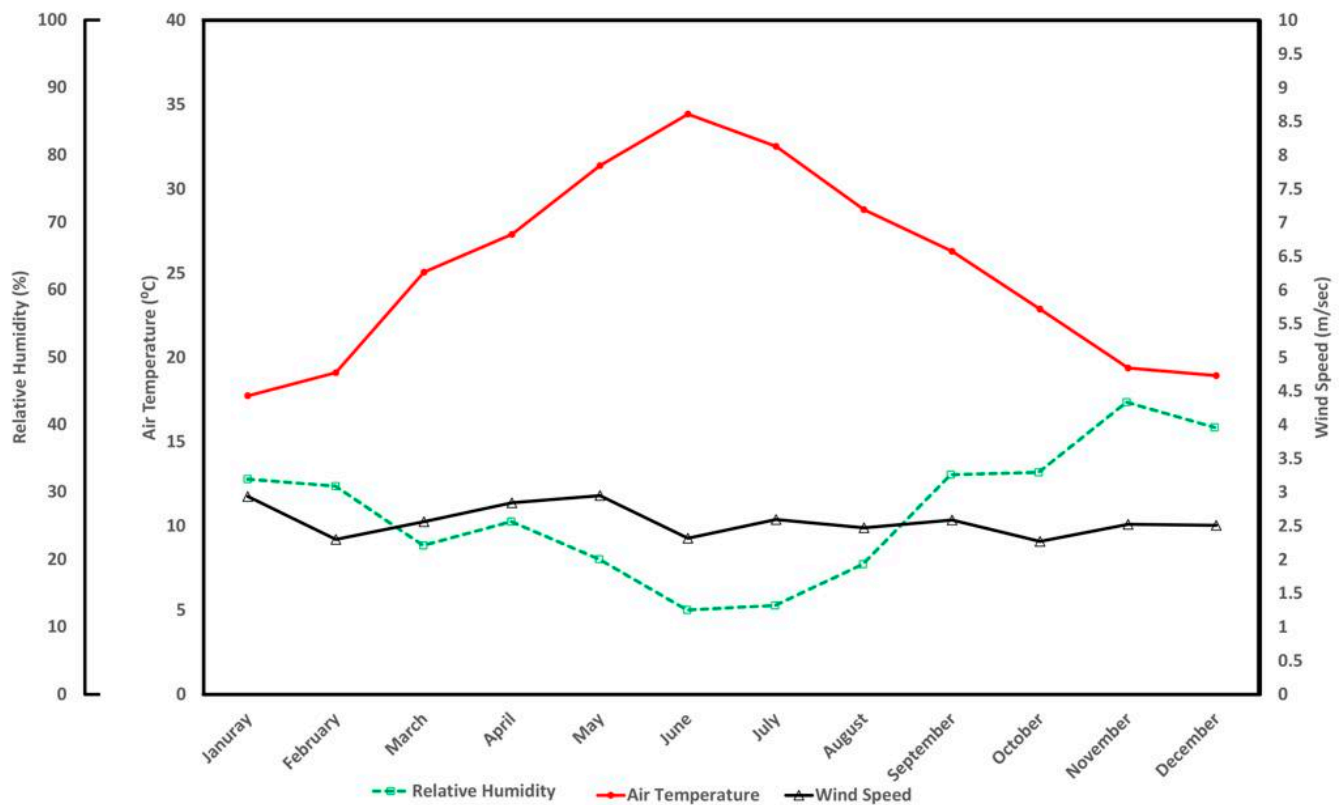


Figure 1. Average monthly weather data for Hail (2018–2021).

3.1.2. Transportation/Societal Data

The method for collecting transport statistics includes a thorough analysis of Hail City's mobility trends and car ownership. The first data for the concepts examined in this study were collected by a questionnaire method, and the local community was provided with access to a Google survey. The survey was conducted by Al-fouzan and Almasri [12] in May 2022, and 346 individuals answered the questions. The questionnaire's objectives were to ascertain residents' mileage, fuel consumption, and acceptance of EVs, as well as to project the preliminary needs for EVCS integration to be sustainable. Google Earth was used as a useful resource to complete this work. The main goal was to gather accurate and current data about the locations of each of these regions, as shown in Figure 2. Table 2 lists and sorts the regions that were gathered, offering a thorough synopsis of the dimensions and percentages of each sector from the total population. In addition to enabling a greater understanding of the city's regional features and facilitating informed decision-making for future developments and resource allocation, these data serve as a crucial foundation for further study and urban planning.

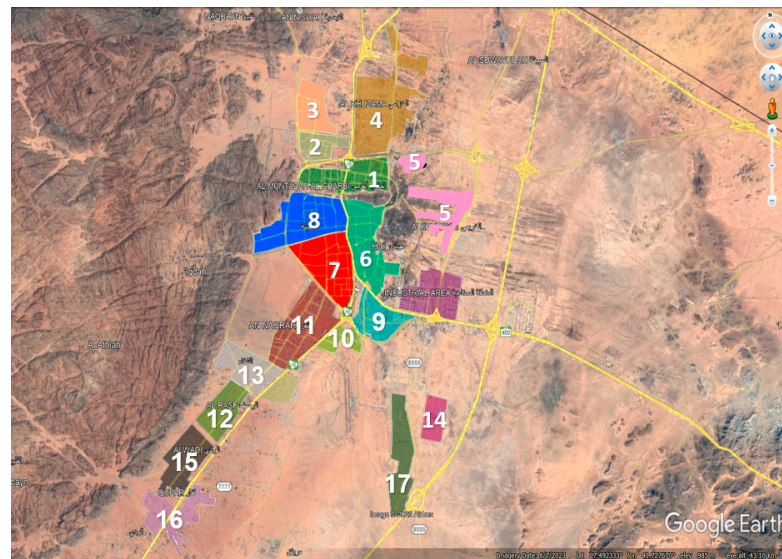


Figure 2. Hail sub-regions. The numbers in the figure shown in the Table 2.

Table 2. Hail sub-region area and population.

Sub-District	Area (ha)	Average Population (%) [44]
1. Al-Muntazah	713	1.58
2. Aja	328	0.48
3. Al-Masyaf	502	0.74
4. Al-Zahraa + Alkhazami + Alyasmeen	1544	22.82
5. Al-Mamlaka	131	0.34
6. Al-Samraa + Az Zibarah + Al-Muzaabar	926	20.52
7. Al-Wosaytaa + Almahata	966	23.20
8. Al-Hanifah	1105	14.29
9. Al-Khamashya	542	5.01
10. Al-Shebily	229	0.25
11. Al-Naqra	1070	1.98
12. Al-Rasf	521	0.58
13. Al-shefaa	597	2.21
14. Soq Al-Mashya	228	1.68
15. Al-Wadi	639	1.18
16. Al-Wudayy	681	0.50
17. Al-Mada'en	716	2.65

3.2. Station Demand

The process of determining the necessary quantity of EVCSs utilizes a thorough and multi-step technique, which is outlined in Figure 3. The results of the poll are combined with demographic information and statistical modeling to create well-informed predictions about EV adoption and the need for EVCSs. The findings can help with infrastructure development, urban planning, and policy choices around EV charging stations and sustainable mobility. The methodology for calculating the number of EVCSs in Hail City involves a multi-step process. It begins with measuring the area of each city zone using Google Earth (version 7.3.6.9345). Population data, combined with survey results on family size, car ownership, and willingness to convert to EVs, inform the number of cars per

zone. The daily battery consumption of EVs is estimated based on average trip lengths and consumption rates. The capacity of charging stations and their ability to serve multiple cars per day are factored in. Finally, the total number of charging stations required is calculated, considering station maintenance and downtime. This approach integrates geographical, demographic, and behavioral data to provide a comprehensive infrastructure estimate for sustainable transport.

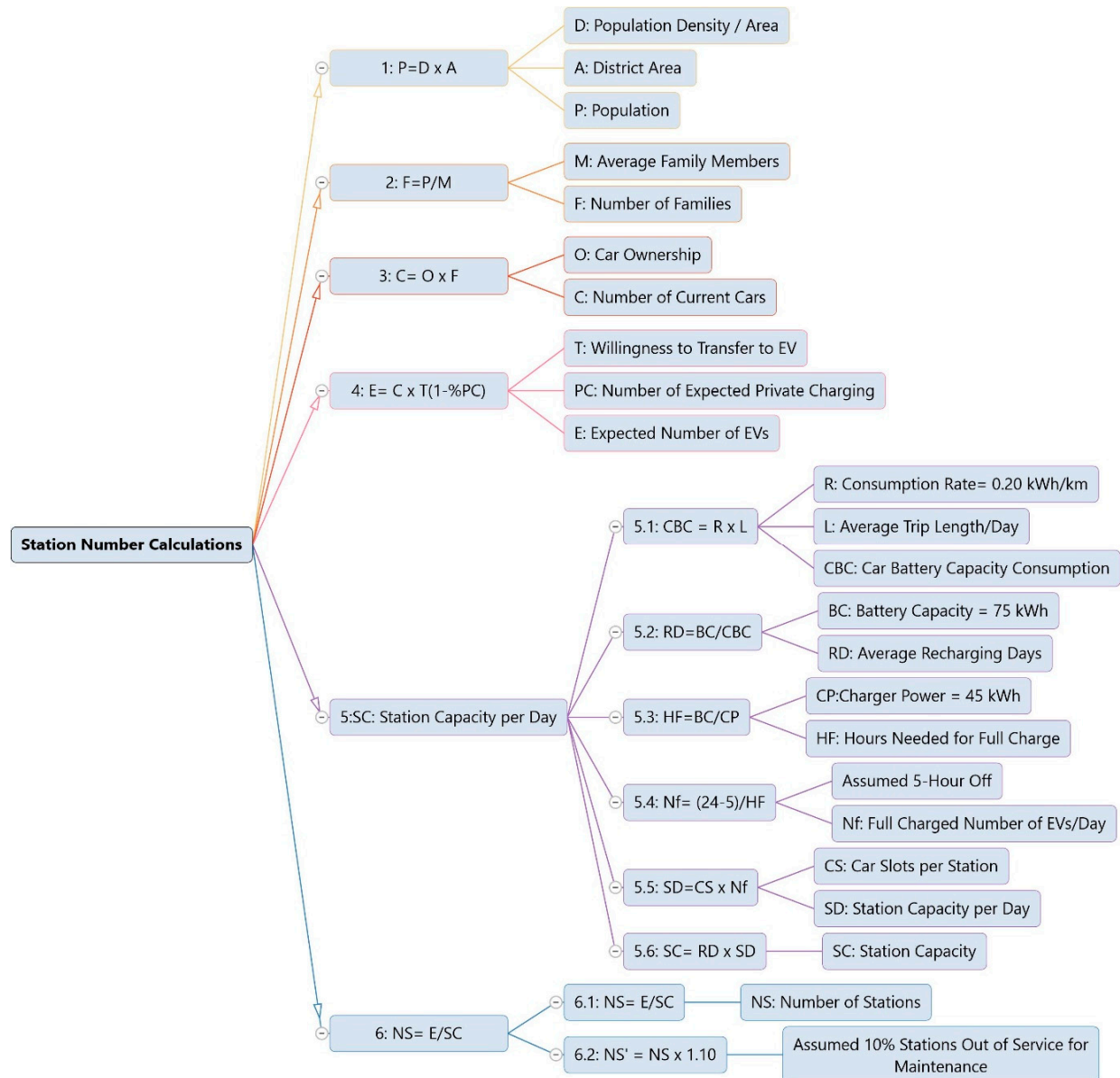


Figure 3. Scheme for performing the number of charging stations calculation.

The geographic area (A) is determined utilizing Google Earth to comprehend the physical domain upon which the ensuing analysis is executed. The average population density (D) is procured through a statistical report [44]. The total population (P) is calculated as demonstrated in Equation (1):

$$P = A \times D \quad (1)$$

The average number of family members (M) is calculated utilizing a weighted average, derived from the questionnaire responses concerning family size. The weighted average equation used is as follows:

$$M = \frac{\sum_{i=1}^N (x_i \times w_i)}{\sum_{i=1}^N (w_i)} \quad (2)$$

where:

x_i = Number of family members in the category,

w_i = Percentage of families in category,

N = Total number of categories.

The total number of families (F) is derived by dividing the total population (P) by the average number of family members (M):

$$F = \frac{P}{M} \quad (3)$$

The average car ownership per family (O) is computed by utilizing a weighted average extracted from the survey data regarding car ownership. The utilized Equation (4) is calculated as demonstrated below:

$$O = \frac{\sum_{i=1}^m (y_i \times v_i)}{\sum_{i=1}^m (v_i)} \quad (4)$$

where:

y_j = Number of cars in the ownership category,

v_j = Percentage of respondents in the ownership category,

m = Total number of ownership categories.

The total number of cars (C) is determined as:

$$C = O \times F \quad (5)$$

The average propensity toward converting to EVs (T) is extracted from the survey data, representing the proportion of respondents indicating a shift toward EV usage. The expected number of EVs (E) is forecasted by multiplying (C) by the average conversion percentage to EVs (T) having the percentage of private charging (PC):

$$E = C \times T \times (1 - \%PC) \quad (6)$$

The usual charging rate is based on the average trip length (L) vs. the EV consumption rate (R) = 0.20 kWh/km as per [45], with approximately 60% of cars being charged at home as per [15,46]. Moreover, the battery capacity (BC) has been set as 75 kWh as an average between 40 and 100 kWh [47].

(L) has been determined based on the conducted survey using the weighted average criteria as follows:

$$L = \frac{\sum_{i=1}^m (L_i \times z_i)}{\sum_{i=1}^m (z_i)} \quad (7)$$

where:

L_i = Trip length per day,

z_i = Percentage of respondents in the trip length category,

m = Total number of ownership categories.

The car battery consumption (CBC) per day is calculated as demonstrated in Equation (8):

$$CBC = R \times L \quad (8)$$

Average recharging days (RD): This measures the frequency of recharging needed for a car. It is calculated as demonstrated in Equation (9):

$$RD = BC / CBC \quad (9)$$

Hours needed for full charge: It is computed by dividing the BC by the charger power CP, which has been assumed to be 45 kWh [48].

$$HF = BC / CP \quad (10)$$

Fully charged number of charging cycles (Nf): This represents the total charging cycles a station can complete in a day. It is calculated by dividing the operational hours of a day (24 h minus 5 h off) by the hours needed for a full charge:

$$Nf = (24 - 5) / HF \quad (11)$$

Station capacity per day (SD): This reflects the daily service capacity of a charging station. It is determined by multiplying the number of car slots per station CS at the station capacity with the number of full charging cycles possible in a day Nf:

$$SD = CS \times Nf \quad (12)$$

Station capacity (SC): This indicates the overall capacity of a charging station over the average recharging day, as follows:

$$SC = RD \times SD \quad (13)$$

Number of stations (NS): The total number of charging stations needed is estimated as follows:

$$NS = E / SC \quad (14)$$

Adjusted number of stations (NS'): Accounts for additional stations needed for maintenance. It is calculated by increasing the NS by 10%.

$$NS' = NS \times 1.10 \quad (15)$$

A parametric study will be conducted by focusing on Al-Wosyataa (number 7), along with the average calculations for all the other zones on the normal average basis assumed in Section 3.2, a central area in the city, due to its significance in terms of population density and urban dynamics. This study aims to analyze the impact of varying key parameters on the required number of EVCSs. The central location of Al-Wosyataa makes it an ideal representative area for this study, as it likely reflects a higher concentration of EV usage and charging needs, providing valuable insights for urban EV infrastructure planning. This study explores all the possible combinations of these parameters, totaling 15,360 cases, as per Table 3.

Table 3. Parametric study initial sample.

EV Consumption Rate R (kWh/km)	Car Battery Capacity BC (kWh)	Car Slots per Station CS (Cars)	Charger Power CP (kWh)
Increased from 0.05 to 0.40 with a step of 0.05	Increased from 25 to 100 with a step of 5	Increased from 50 to 500 with a step of 50	Studied from 20 to 75 with a step of 5

In analyzing the EV charging infrastructure requirements across the 17 different zones of Hail, a standardized set of assumptions has been employed, see Table 4. This approach provides a foundational overview of the charging station needs in each zone, facilitating a comprehensive understanding of the infrastructure demands. In addition to these standard

assumptions, a key practical consideration is incorporated to reflect real-world charging behaviors: the assumption is that 60% of EVs will be via private chargers, according to Bailey et al. [17] and Almutairi [15].

Table 4. A standardized set of assumptions.

EV Consumption Rate R (kWh/km)	Car Battery Capacity BC (kWh)	Car Slots per Station CS (Cars)	Charger Power CP (kWh)
0.20	75	200	45

3.3. Technical Analysis

In evaluating the PV module type for this study, factors such as the performance, warranty, and availability in the local market are considered [49]. The choice to use Jinko Solar modules in the design of the solar charging stations is influenced by their suitability for the environmental conditions and their high module efficiency [50]. The Jinko Solar modules, specifically designed for such applications, have a high efficiency rate, adhering to the relevant industry standards, including IEC 61215 [51] and IEC 61730 [52]. The specifications of these modules are detailed in Table 5. The lifespan of the project is aligned with that of the modules, estimated at 30 years.

Table 5. The PV module specifications [50].

PV Panel Type	N-Type Mono-Crystalline
Maximum Power at STC (Wp)	615
PTC Power Rating (W)	462
Manufacturer	Jinko Solar
Optimum Operating Voltage (Vmp)	45.69 V
Optimum Operating Current (Imp)	13.46 A
Open-Circuit Voltage (Voc)	55.40 V
Short-Circuit Current (Isc)	14.18 A
Module Efficiency	22.00%
Nominal Operating Cell Temperature (°C)	45–85
Application Classification	Class A

In the solar charging station at LuLu’s Marketplace, the PV array was equipped and tailored to meet the energy requirements of the EVCSs. The setup will involve an appropriate number of grid inverters to efficiently convert solar energy into usable electrical power for charging EVs. The exact configuration, including the number of inverters and their type, will be determined based on the total capacity of the PV array installed at the station. It is important to consider the effect of the cell temperature (T_c) on the efficiency of the PV array. The real impact of the T_c on the efficiency of the PV panels, particularly during the peak summer season, is crucial to determine the actual energy contribution to the charging process. The average efficiency (η_e) of the array is evaluated as a function of the average module T_c , using the following equation to assess the efficiency variation under different temperature conditions:

$$\eta_e = \eta_R [1 - (T_c - T_R)] \quad (16)$$

To calculate the array’s average efficiency (η_e), the PV module efficiency (η_R) at reference temperature (T_R) and the temperature coefficient for module efficiency (μ) are taken from the PV module datasheet. The calculated average efficiency (η_e) for the PV array is 19% when the reference efficiency is 22%. The T_c is connected to the mean ambient

temperature T_a and the nominal operating cell temperature, as shown in Equation (17), as follows. In the following equation, G_t is expressed in W:

$$T_c - T_a = \left(\frac{NOCT}{800} \right) G_t \quad (17)$$

In the context of the solar charging station at LuLu's Marketplace, the energy output from the PV array is a crucial parameter. This output is determined by the area (A) of the PV array, which is equipped with modules, and includes considerations for various losses in the system. These losses are categorized as various PV array losses (L_m) and power conditioning losses (L_c). For this study, we assume L_m to be 2% and L_c to be 1.5%. These percentages reflect the expected efficiency reduction due to factors such as dust accumulation, temperature effects, and inefficiencies in the energy conversion process from solar to electrical energy.

The daily average global radiation on the slanted surface of the PV modules, denoted as G_t (kWh/m²), is a critical factor in determining the array's energy output. This radiation value is essential for calculating the actual energy that can be harnessed by the solar array under specific climatic conditions. Equation (18) provides a comprehensive view of all these parameters, detailing the method for calculating the daily energy production of the PV array.

$$EA = \eta_e A G_t (1 - L_m)(1 - L_c) \quad (18)$$

The energy that is provided to the grid while there is no load is shown in Equation (19):

$$E_{grid} = EA \eta_{inv} \quad (19)$$

The annual energy output on the AC grid side can be calculated by integrating the output power over time and accounting for system losses, including inverter efficiency:

$$E_{annual} = \sum (P_{module} \times \eta_{Inverter}) \times 8760 \times LF \quad (20)$$

where:

$\eta_{Inverter}$: The efficiency of the inverter (as a decimal),

8760 is the number of hours in a year,

LF: The load factor, representing the fraction of the year the system operates at nominal capacity.

After calculating the yearly energy input into the grid, the performance indicator is calculated as demonstrated in Equation (21):

$$YF = \frac{E_{grid} \text{ (kWh/year)}}{PV \text{ array (kW/peak at STC)}} \quad (21)$$

The location of LuLu's Hypermarket and the plan view before the installation of the PV system, as shown in Figure 4, is chosen as the ideal location to create a model EVCS because of its east access through the main mall area. The purpose of installing a carport and roof-mounted solar PV system at this location is to serve as a prototype for similar configurations in urban areas. This demonstration intends to illustrate how these stations may effectively meet the increasing need for EV charging while encouraging the use of sustainable energy. The technical process involves evaluating the amount of solar radiation present, the system's ability to capture energy, and the actual output when taking into account elements like the shade, module orientation, and inclination. Furthermore, this study includes an assessment of the energy allocation among direct use, charging of EVs, and feeding energy back into the grid. This research offers a thorough comprehension of the system's capability and effectiveness in real-life scenarios, which is essential for sustainable energy solutions in commercial settings. The structured breakdown of the procedures and

calculations used in determining the solar PV system performance of the carport and the rooftop-mounted system is as follows:



Figure 4. LuLu's Hypermarket location (a), and plan view before the PV unit installation (b).

Step 1: Solar radiation and PV module area

Step 2: PV generator output

Step 3: PV system performance (yield factor (kWh/kWp) and performance ratio (PR) (%))

Step 4: Energy production and use

- PV generator energy (AC Grid): Total energy output transferred to the AC grid,
- Direct own use: Energy directly used from the PV system,
- Charge of EVs: Energy used to charge EVs,
- Grid Feed-in: Excess energy supplied back to the grid.

Step 5: Auxiliary consumption and system losses

It should be emphasized that the overall energy generation estimates provided by $PV \times SOL$ may not precisely align with the theoretical calculations. This is because the program considers panel degradation over time and all the potential losses, resulting in a more precise and realistic estimation of the system performance. The power output of a PV module can be calculated using the following equation:

$$P_{module} = \frac{G \times A \times \eta_R}{1000} \quad (22)$$

where:

G: The solar irradiance on the module (W/m^2),

A: The area of the PV module (m^2),

η_R : The efficiency of the PV module (%).

The factor of 1000 converts the result from (W) to (kW).

Following the comprehensive study of four key parameters (R, BC, CS, and CP), the focus will shift to analyzing four performance parameters. These performance parameters are critical when assessing the overall efficiency and effectiveness of the EV charging infrastructure and vehicle performance. The study of these parameters will provide deeper insights into the operational aspects of the EV ecosystem.

3.4. Economic Analysis

The decision was made to focus on a single solar charging station, specifically one located at LuLu's Marketplace. The initial analysis identified the need for a network of stations across 17 different zones. By concentrating on one strategically selected station, this study aims to provide a detailed and thorough investigation of the economic, technical,

and environmental parameters. This approach not only allows for a more manageable and focused analysis but also serves as a representative model. The findings and methodologies applied to this single station can then be extrapolated or adapted for broader application across the proposed network, offering valuable insights for the potential scalability and replication of the project in other zones or similar urban contexts.

In the economic analysis of the solar charging station for EVs, the LCOE and net present value (NPV) metrics are utilized to evaluate the project's financial viability. Given the long-term nature of the solar charging station project, the real LCOE is employed in this study. Equation (23) outlines the methodology for calculating the LCOE:

$$LCOE(real) = \frac{-C_0 - \frac{\sum_{n=1}^N C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^N Q_n}{(1+d_{real})^n}} \quad (23)$$

where:

C_0 : Equity investment (USD),

C_n : Project's cost in n years,

d_{real} : Real discount rate (%),

$d_{nominal}$: Nominal discount rate (%), see Equation (24),

N : Analysis period in years,

Q_n : Amount of electricity generated by the plant in year n. (kWh).

$$NominalDiscountRate = \left[\left(1 + \frac{RealDiscountRate}{100} \right) \times \left(1 + \frac{InflationRate}{100} \right) - 1 \right] \times 100 \quad (24)$$

The NPV is a popular metric used to gauge a project's cost-effectiveness. The cost-effectiveness metric known as the NPV of a project combines both cost and income. Equation (25) can be used to determine the NPV. A project is said to be economically viable if its NPV is positive, as opposed to being unviable if it is negative.

$$NPV = \sum_{i=0}^N \frac{(Cash\ flow)_i}{(1+d)^i} \quad (25)$$

N is the number of years that the installation will last, and the installation's lifespan is represented by the I ; $I = 1$ to 30.

The PBT will be estimated as an economic performance measure, which can be calculated as follows:

$$PBT(Years) = \frac{Initial\ Cost}{\left(E_{grid} \left(\frac{kWh}{year} \right) * Value_{(SR\ or\ USD / kWh)} - C_{O\&M} \left(SR\ or\ \frac{USD}{kWh} \right) \right)} \quad (26)$$

The concept of the return on assets (ROA) is pivotal for assessing the financial efficiency of companies involved in PV system design and implementation. The ROA is calculated using the following equation:

$$ROA = \frac{Net\ Income}{Total\ Assets} \quad (27)$$

- Net income represents the profit of the company after all the expenses and taxes have been deducted.
- Total assets encompass the sum of all the assets owned by the company, including both current assets and fixed assets like PV equipment and infrastructure.

The amount that lowers a project's NPV to zero is known as the discount rate. It is the anticipated compound annual rate of return on a project or investment. The PV * SOL is used to estimate an investment's internal rate of return.

According to the study, the Saudi Central Bank reports an interest rate of 2.4% and an inflation rate of 2.5%. All the same, a 4.5% discount rate is expected for the KSA. The project would take 30 years to complete, which is equivalent to the life cycle of a PV module. Debt would not be included in the project's capital costs. On average, inverters have a 15-year lifespan and can be recovered for 30% of their original cost. In December 2019, a regulation was produced by the Electricity and Cogeneration Regulatory Authority [53]. The installation, maintenance, and operation of small solar PV energy systems in all installations are certified by this legal framework. The export price set by the government for surplus energy generated by photovoltaic systems in the non-residential sector is SR 0.05 (USD 0.013) per kWh, whereas the power tariff for the commercial sector is SR 0.20 (USD 0.075) per kWh [54]. The PV * SOL was used to model the projected PV system and change the export tariff from 0.05 to 0.32 SR/kWh. The goal is to ascertain whether it is appropriate and financially feasible to raise the government's official export tariff as part of a PV incentive package.

3.5. Environmental Analysis

Implementing PV charging for EVs will result in significant carbon dioxide (CO₂) emission reductions. These reductions are influenced by the number of EVs, the efficiency of PV panels, and the percentage of the grid powered by PV. Additionally, varying the energy consumption rate of EVs impacts the overall CO₂ savings. Table 6 describes the parameters used. The annual CO₂ reduction is calculated according to the relationship:

$$CO_2 \text{ Reduction}_{Fuel} = \frac{(FR \times CFR + CER \times R \times PVE \times \text{Share of EVCS}) \times E \times L \times 365}{1000} \quad (28)$$

where:

- FR: Average vehicle fuel consumption rate (L/100 km),
- CFR: CO₂ emission per liter of fuel (kgCO₂/L),
- CER: CO₂ emission per kWh of electricity (kgCO₂/kWh),
- PVE: PV system efficiency (%),
- Factor 1000 (conversion to MtCO₂),
- Factor 365 (number of days per year).

Table 6. Environmental parametric study.

Parameter	Description	Values
Fuel Consumption Rate	Average fuel consumption of vehicles	9.02 L/100 km [55]
CO ₂ Emissions from Fuel	CO ₂ emissions per liter of fuel	2.28 kg CO ₂ /L [56]
CO ₂ Emissions from Electricity	CO ₂ emissions per kWh of electricity	0.75 kg CO ₂ /kWh [57]
EV Consumption Rates	Energy consumption rates of EVs	0.15, 0.20, 0.25, 0.30 kWh/km [58]
Number of EVs	Scale of EV adoption	1000; 10,000; 50,000
PV Efficiency	Efficiency of PV panels	100% (initial), (88% at the end of life)
Share of PV-EVCS	Proportion of grid powered by renewables	20%, 80%

4. Results and Discussion

This section looks at and evaluates the research's findings and suggests a course of action for building a solar charging network, particularly for Hail City. The data are combed through to identify significant trends that may have an impact on the development of an efficient, sustainable, and user-friendly infrastructure for EV charging. Enabling a seamless transfer from raw data to actionable insights is the aim, and it may be achieved with a clear and straightforward approach to the deployment of a robust SCSN. The upcoming sections will examine various aspects of the research findings,

offering a comprehensive examination and discussion of the on-site decisions, design standards, and technology integrations.

4.1. Societal and Behavioral Parameters

Al-fouzan and Almasri [12] measured several parameters to assist in the creation of a forecast model for the adoption of EVs in the future. The weighted average values of the indicators were determined using Equations (7) and (9). The results of the poll were analyzed concerning the status of the transportation sector, the level of social acceptance of EVs, and the infrastructure needed for charging. The authors reported that one car is owned by 25% of the sample, and the same proportion owns two cars. According to 8.1% of respondents, there are more than six cars at home, which is consistent with research by Almutairi [15]. The results show that roughly 5.8 people are living in each Hail household on average, which is in line with the data reported by Esmaeil et al. [59]. According to Almasri et al. [60], there were 7.3 family members in the Qassim region of the KSA. The data reported by Almutairi [15] are consistent with the average car ownership of 3.15 cars per household, which suggests a strong reliance on personal vehicles for mobility purposes. The weighted average monthly income of the households polled, measured in terms of economic characteristics, is SR 13,350. Just 1.4% of respondents reported receiving a car from their employer, whereas 98.6% of respondents said they had a personal vehicle. The average amount of time spent driving each day is 2.1 h, which indicates a high usage of personal vehicles for everyday commuting and other activities. In terms of money, the respondents pay SR 235 for fuel on average every week.

In terms of the travel distances, the average daily journey length is roughly 77.55 km, indicating a significant daily reliance on private vehicles for transportation. On highways, the average driving speed rises to 116.5 km/h, whereas in urban areas, it is approximately 66.95 km/h. A greater proportion, 47.1%, stated that they are considering purchasing an EV in the future. This suggests that interest in EVs is expanding, which is consistent with research by Almutairi [15]. To obtain more data about citizens' behavior regarding EVs and their CSs in Hail, see Al-fouzan and Almasri [12].

4.2. Station Number

A thorough examination of Hail City's anticipated automobile scene for 2030 was carried out, utilizing market knowledge and projections from multiple reliable sources. According to [44], Hail City's population will increase to 582,152 by 2030. Hail City is expected to hold roughly 2.3% of Saudi Arabia's automobile market, according to [61]. Moreover, according to data from [62], the private automobile segment accounts for roughly 53.8% of the entire market. Figure 5 shows data for the transportation sector in the KSA in 2019 and 2022. When these observations are combined with an evaluation of the typical neighborhoods and family car ownership, a preliminary projection indicates that by 2030, Hail City will have about 250,000 cars. However, a more refined calculation, taking into account the average family size and the expected population growth, suggests that the total number of cars could realistically approach 304,000. This figure is detailed in Table 7. This illustrates the potential scale of automotive ownership in the context of Hail City's urban development and provides a solid foundation for further analysis of the SCSN's requirements to be sustainable.

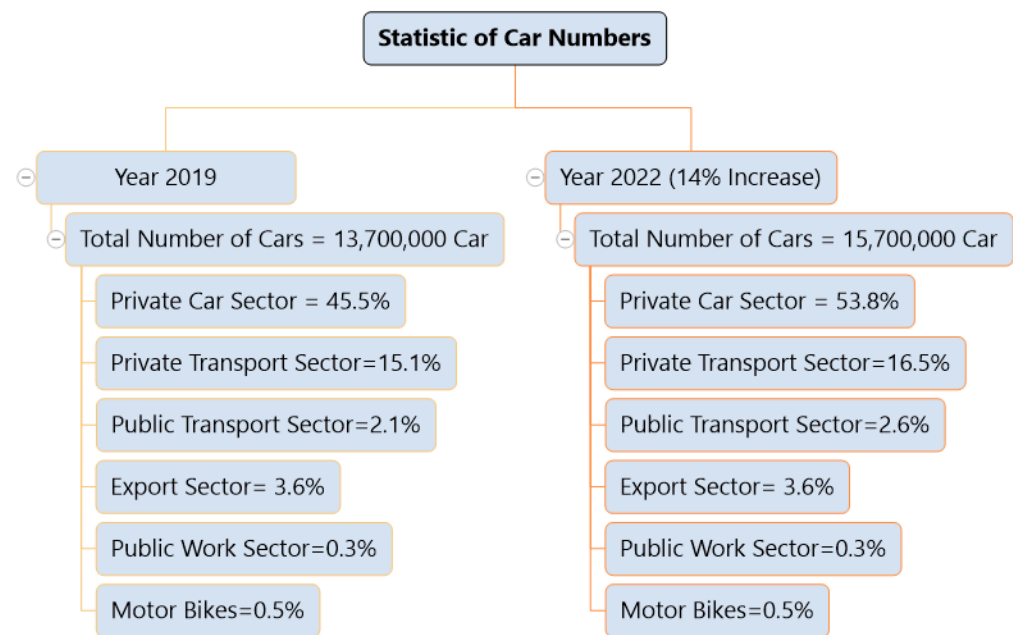


Figure 5. Car statistics in Saudi Arabia [62].

Table 7. Estimated number of cars (zonal).

Zone Name	Car Numbers	Zone Name	Car Numbers
1. Al-Muntazah	4938	10. Al-Shebily	795
2. Aja	1517	11. Al-Naqra	6176
3. Al-Masyaf	2320	12. Al-Rasf	1805
4. Al-Zahraa + Alkhazami + Alyasmeen	71,273	13. Al-shefaa	6891
5. Al-Mamlaka + AlKhuraymi	1059	14. Soq Al-Mashya	5266
6. Al-Samraa + Az Zibarah + Al-Muzaabar	64,118	15. Al-Wadi	3689
7. Al-Wosaytaa + Almahata	64,101	16. Al-Wudayy	1574
8. Al-Hanifah	44,634	17. Al-Mada'en	8265
9. Al-Khamashya	15,639	Total	304,060

For the scenario with no private charging adoption, the highest concentration of charging stations was required in the central areas of Hail City. Based on what was explained in Section 3.2, the number of stations and the influencing factors were determined. Specifically, Zone 4 necessitated the maximum NS', totaling seven, followed closely by Zones 6 and 7, each requiring six stations. This pattern aligns with the expected higher demand for public charging facilities. Conversely, when the model incorporated a 60% PC rate, reflecting a substantial adoption of private charging solutions, there was a marked decrease in the demand for public charging stations. In this scenario, the NS' in Zone 4 was reduced to four, while Zones 6 and 7 each showed a decrease to three and four stations, respectively. Table 8 shows the adjusted number of PV charging stations for each region as a function of the PC ratio from 0% to 60%. It is important to note that, regardless of the PC rate, a minimum of two stations per zone is maintained to ensure operational reliability and to account for maintenance needs. This baseline ensures that even in zones with a lower demand, EV users have consistent access to public charging options.

Table 8. Expected PV charging stations (adjusted–NS') in Hail City.

Home Charging	0%	20%	40%	60%
Zone 1	2	2	2	2
Zone 2	2	2	2	2
Zone 3	2	2	2	2
Zone 4	7	6	5	4
Zone 5	2	2	2	2
Zone 6	6	5	4	3
Zone 7	6	5	4	3
Zone 8	5	4	3	3
Zone 9	3	2	2	2
Zone 10	2	2	2	2
Zone 11	2	2	2	2
Zone 12	2	2	2	2
Zone 13	2	2	2	2
Zone 14	2	2	2	2
Zone 15	2	2	2	2
Zone 16	2	2	2	2
Zone 17	2	2	2	2

4.3. Technical Results

The analysis within this work was conducted using the PV * SOL Premium Simulator (version 2024 R3) to assess the impact of solar integration on EV charging capabilities and to design an example of an EVCS implementing PV energy. Feasibility modeling for the installation of solar PV at LuLu's Hypermarket in Hail revealed several important characteristics regarding the module areas. Table 9 presents a summary of the solar array installations in various regions of the facility. The data provided include information regarding the overall surface area occupied by the arrays, as well as the quantity of modules deployed in each specific part. The system is composed of 1703 PV modules. The output of the PV generator is calculated scientifically based on the individual output capacity of each module with a capacity of (1703×0.615) 1047.35 kWp. Eight inverters, each with a capacity of 8 kW, were used to charge 600 cars per day. Figure 6 illustrates the intricate design of the carport and roof-mounted solar PV systems. The annual available energy with solar radiation on the solar cell field can be calculated as follows:

$$2222.11 \text{ kWh/m}^2 \times 4760.41 \text{ m}^2 = 10,578,164.61 \text{ kWh}$$

Table 9. PV array and number of module installations in LuLu's Hypermarket EVCS.

Area Description	Total Surface Area (m ²)	Number of Modules
Roof	3552.8	1271
Carport 01	$150.9 \times 2 = 301.8$	$54 \times 2 = 108$
Carport 02	$201.3 \times 2 = 402.6$	$72 \times 2 = 144$
Carport 03	$251.6 \times 2 = 503.2$	$90 \times 2 = 180$
Total Combined PV Module Area	4760.4	1703

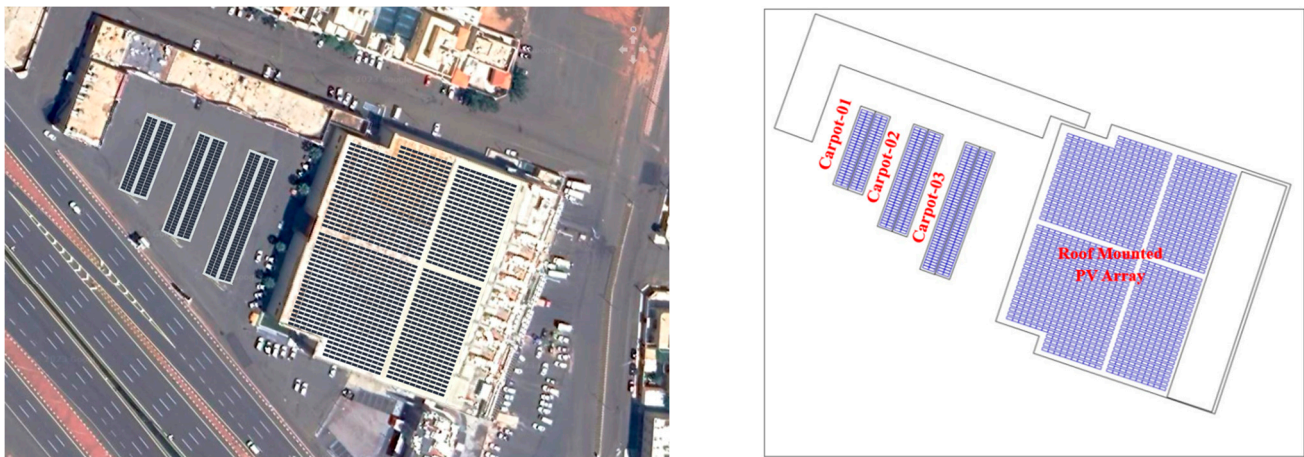


Figure 6. PV general layout (1047.35 kWp system).

Table 10 provides detailed information on the PV system. The total annual energy output is 2,054,029 kWh, with 1,629,534 kWh used for charging EVs, 416,199 kWh fed into the grid, and 8295 kWh used directly, which means that the solar fraction is 66.1%. In its first year, including the effects of module degradation, the system is projected to feed 415,062 kWh into the grid. This ties into the total annual energy output previously detailed, with significant portions allocated to direct use and EV charging, as well as a specified portion fed back into the grid. Over the assessment period of 30 years, the system's performance metrics, including a yield factor of 1961.04 kWh/kWp and a high PR of 88.2%, demonstrate its efficiency and reliability in converting solar energy into usable power. The minimal impact from shading, at just 0.3% per year, indicates an optimal setup with negligible losses due to environmental factors. Financially, the system carries an interest on capital of 1%, reflecting the investment's cost over time. This interest rate will affect the overall financial returns, especially when considering the long-term energy production versus operational and maintenance costs.

Table 10. System data.

Start of Operation of the System	10/5/2023
Grid Feed-in in the First Year (incl. Module Degradation)	415,062 kWh/Year
PV Generator Output	1047.3 kWp
Assessment Period	30 Years
Interest on Capital	1%
PV Generator Energy (AC grid)	2,054,029 kWh
Direct Own Use	8295 kWh
Charge of the EV	1,629,534 kWh
Grid Feed-in	416,199 kWh
Down-regulation at Feed-in Point	0 kWh
Auxiliary Electricity Consumption (Annual)	11,692 kWh
Own Power Consumption	79.7%
Solar Fraction	66.1%
Yield Factor	1961.04 kWh/kWp
Performance Ratio (PR)	88.2%
Yield Reduction due to Shading	0.3%/Year
CO ₂ Emissions Avoided	1,540,522 kg/year

The energy balance of the PV system for the LuLu’s Hypermarket solar project has been analyzed using data to assess the overall performance and efficiency of the PV system. Starting from this initial potential, the system experiences multiple reductions as a result of intrinsic physical and operational inefficiencies. Table 11 shows basic information for the PV system using the PV * SOL. The module efficiency, as rated under the STC, is notably 22.01%. This results in a useful energy output of precisely 2,327,960.48 kWh. The calculation takes into consideration additional losses, such as the partial shading particular to each module, improvements in low-light performance, temperature variations, and losses caused by diodes and mismatches in module information and setup. Through a sequence of deductions, the amount of DC energy is reduced to 2,140,035.33 kWh before being regulated by the inverter. The AC output of 2,053,887.35 kWh is achieved through further modifications made at the inverter stage to compensate for voltage variations and conversion inefficiencies. When taking into account small regulatory and standby consumptions, the output is adjusted to 2,054,029.01 kWh. The specific analyses of these values and their individual effects are methodically organized in the corresponding energy balance, shown in Table 12, providing a clear perspective on how each element and environmental factor contributes to the overall energy output of the system.

Table 11. PV * SOL general output.

Charge at beginning	38,442	kWh
Charge of the EV (Total)	2,466,604	kWh/Year
Charge of the EV (PV System)	1,629,534	kWh/Year
Charge of the EV (Grid)	837,070	kWh/Year
Discharging the EV for consumption	0	kWh/Year
Losses due to charging/discharging	350,776	kWh/Year
Losses in battery	271,966	kWh/Year
Consumption due to kilometers driven	1,882,305	kWh
Mileage per year	10,950,000	km
of which is solar	7,233,994	km

Charge of the electric vehicle (Total)

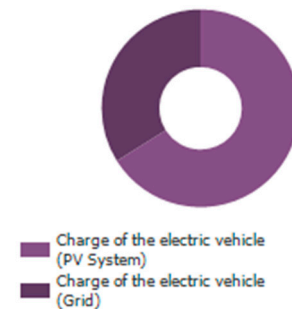


Table 12. PV System energy balance.

Global radiation–horizontal	2170.32	kWh/m ²	
Deviation from the standard spectrum	−21.70	kWh/m ²	−1.00%
Ground reflection (albedo)	3.26	kWh/m ²	0.15%
Orientation and inclination of the module surface	70.23	kWh/m ²	3.26%
Global radiation at the module	2222.11	kWh/m ²	
Global PV radiation	10,578,164.61	kWh	
STC conversion (rated efficiency of module: 22.01%)	−8,250,204.13	kWh	−77.99%
Rated PV energy	2,327,960.48	kWh	
Module-specific partial shading	−5618.23	kWh	−0.24%
Low-light performance	16,103.81	kWh	0.69%
Deviation from the nominal module temperature	−153,548.80	kWh	−6.57%
Diodes	−361.45	kWh	−0.02%
Mismatch (manufacturer information)	−43,690.72	kWh	−2.00%

Table 12. *Cont.*

Mismatch (configuration/shading)	−809.77	kWh	−0.04%
PV energy (DC) without inverter down-regulation	2,140,035.33	kWh	
Down-regulation on account of the max. AC power/cos phi	−37,060.38	kWh	−1.73%
MPP matching	−3182.46	kWh	−0.15%
PV energy (DC)	2,099,792.42	kWh	
Energy at the inverter input	2,099,792.42	kWh	
Input voltage deviates from the rated voltage	−5852.06	kWh	−0.28%
DC/AC conversion	−39,911.35	kWh	−1.91%
Standby consumption (inverter)	−141.66	kWh	−0.01%
PV energy (AC) minus standby use	2,053,887.35	kWh	
PV generator energy (AC grid)	2,054,029.01	kWh	

4.4. Site Spatial Parametric Study

In this research, a Quantum Geographic Information System with OpenStreetMap data and the Open Route Service (ORS) were employed, and questionnaire data were used to analyze and determine the average travel distances for various driving scenarios in Hail City. The analysis encompassed different zones—north, middle, and south—within the city. It was found that the average driving distance within these zones extends up to 37 km. Consequently, this distance has been adopted as the upper limit for the study, ensuring that the research accurately reflects the typical driving patterns. Table 13, outlining the trip durations in hours for these lengths, offers a more granulated perspective. In the conducted study, the ORS was utilized to ascertain both the fastest and shortest routes for various travel scenarios within Hail City. This approach enabled an evaluation based on the average distances, aligning with the specific objectives of the research. In correlation with L , determined to be approximately 77 km/day through a comprehensive survey, it was observed that a maximum one-way distance of 37 km, accounting for a round trip of approximately 74 km, corroborates the survey findings. This concurrence between the ORS-derived data and the survey results substantiates the accuracy of the average distances used in the analysis, providing a robust foundation for the study's conclusions. Such a methodology underscores the effectiveness of integrating advanced geospatial tools with empirical data collection in urban transportation research.

Table 13. Summary of trip lengths and time for possible common driving scenarios in Hail City.

	Shortest Distance (km)	Shortest Period (hr)
North to North	16.00	0.335
North to Middle	24.73	0.444
Middle to Middle	9.581	0.164
Southern to Northern	37.77	0.564
Southern to Middle	16.00	0.324
Southern to Southern	19.35	0.291

4.5. Economic Results

In the study presented, a 1047.35 kWp PV system, encompassing both carport and roof-mounted configurations, was evaluated for its capacity to charge EVs. The system primarily relies on solar energy during sunlit hours, while the local grid supplements power during the evening or night-time hours. Excess solar energy, generated when EVs are not being charged during the daytime, is fed back into the electricity grid. Various EV chargers,

with capacities ranging from 22 kW to 220 kW, were considered in the analysis. The range of chargers was selected to accommodate different categories of EVs. The solar PV modules employed in the system are Tier 1, offering an efficiency of 22% and compatibility with local weather conditions, including potential induced degradation resistance.

Economic parameters such as the return on assets, accrued cash flow, PBT, and electricity production costs are meticulously outlined to provide a comprehensive understanding of the financial viability of the project. Table 14 shows the cost of consuming electricity from the national grid and the financial cost of feeding the grid in the event of a surplus of energy from the system. The results show that the PBT is 11.69 years and the LCOE is 0.085 SR/kWh. Table 15 details the specific investment costs, including the breakdown of the investment in the solar PV system and EVCSs, as well as the operational and maintenance costs. The impact of the system on electricity savings, and other revenues or savings is quantitatively assessed. This is complemented by a summary of the remuneration and savings, including the total payments from utilities and first-year savings. Moreover, the feed-in tariff and energy tariff information, along with their respective validity periods and rates, are presented to provide a complete financial perspective on the project. These tables are crucial for understanding the economic aspects of the system and its potential for reducing travel costs and contributing to environmental sustainability. Figure 7 provides a detailed breakdown of the cash flow analysis for the grid-connected PV system with EV charging capabilities, spanning 30 years. This comprehensive financial projection includes yearly data on investments, revenues from feed-in/export tariffs, electricity savings (both from solar energy and grid), operational and maintenance costs, EV charging tariffs, and warranty performance. Key metrics such as the annual and accrued cash flow are meticulously calculated for each year, presenting a thorough understanding of the system's economic performance over time. This analysis is pivotal to assessing the long-term financial sustainability and profitability of the project, providing insights into the return on investment and the overall financial health of the solar charging station initiative.

Table 14. Remuneration costs.

Validity	10/5/2023	10/4/2053
Specific Feed-in/Export Remuneration	0.05	SR/kWh
Energy Tariff (Saudi Electricity Company)		
EV Charging Price	0.20	SR/kWh

Table 15. Economic parameters.

ROA	10.17	%
Specific Investment Costs	4285.08	SR/kWp
Investment Costs	4,487,982.00	SR
Solar PV System Installation Cost	2,147,057.00	SR
EV Charging Stations Cost	2,340,925.00	SR
Operational and Maintenance Cost (O&M)	50,000.00	SR/Year
Total Payment from Utility in the First Year	20,809.95	SR/Year
First-Year Savings	325,906.80	SR/Year
Accrued Cash Flow (Cash Balance)	7,169,294.62	SR
PBT	11.69	Years
LCOE	0.085	SR/kWh
Travel Cost without PV	5.79	SR/100 km
Travel Cost with PV	2.47	SR/100 km

the number of EVs, regardless of the PV-EVCS share. This highlights how crucial it is to increase the efficiency of EVs and the proportion of PV in the infrastructure used for charging them to maximize the reduction of CO₂ emissions. The yearly reduction in CO₂ emissions was computed for various EVs (ranging from 1000 to 50,000 cars) with variable rates of R (0.15 to 0.30 kWh/km) in MtCO₂/year, see Table 16.

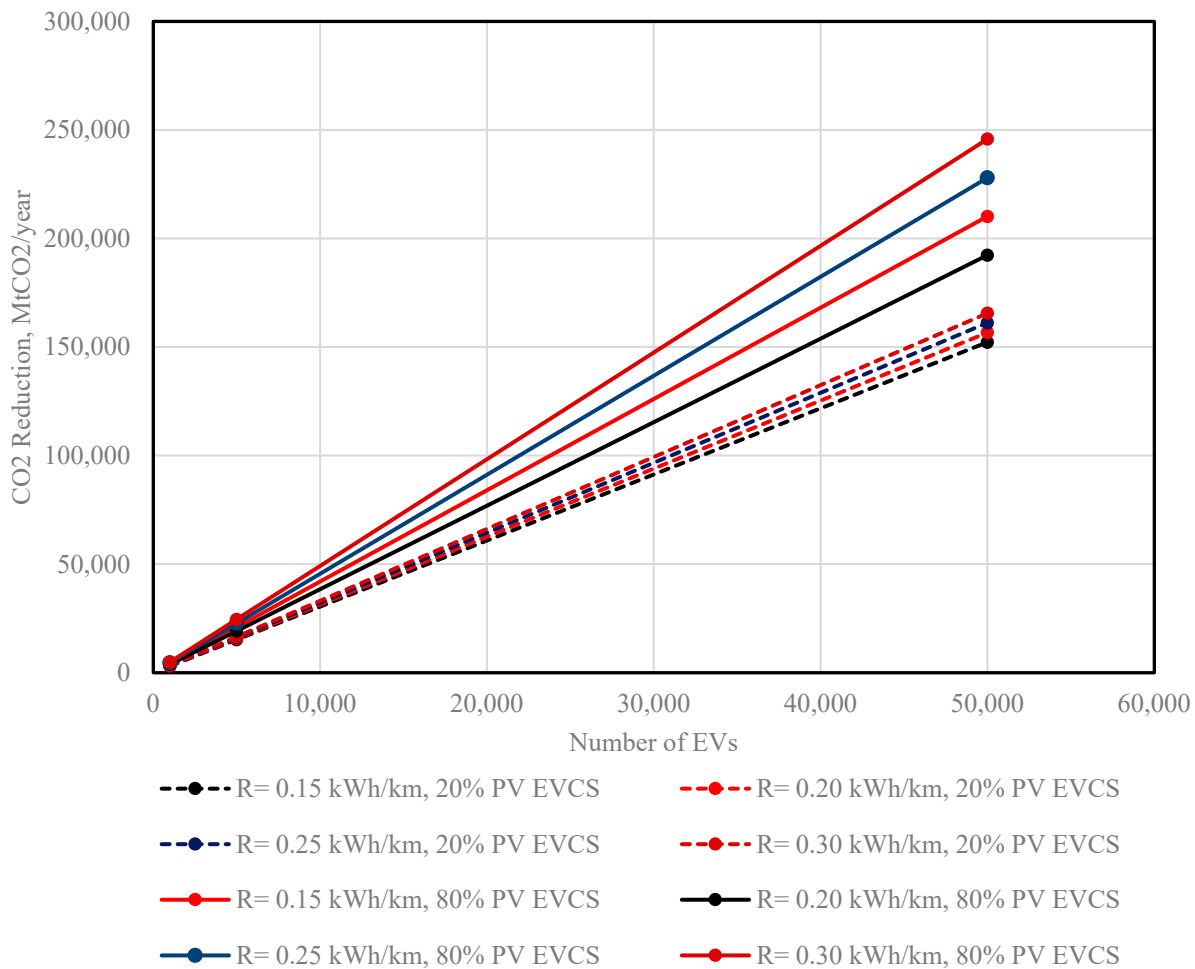


Figure 9. CO₂ reduction scenarios.

Table 16. CO₂ savings for different numbers of EVs and R in (MtCO₂/year).

PV Share (%)	R (kWh/km)	Numbers of EVs (Cars)	
		1000	50,000
80	0.15	3847	192,349
	0.30	4917	245,829
20	0.15	3045	152,239
	0.30	3312	165,609

5. Limitations

The investigation of the attitudes toward and potential for EV integration in a rapidly urbanizing city underscores the necessity of sustainable transportation solutions. Through a combination of survey-based analysis and strategic evaluation of charging infrastructure needs, this study illuminates the prospects of EV adoption in the context of escalating urbanization and environmental challenges. However, the research is subject to certain limitations that are crucial for contextualizing its outcomes and guiding subsequent inquiries.

These limitations stem from a range of factors specific to the urban landscape under study and may not be applicable across different settings.

1. **Geographical and Climatic Specificity:** This study's primary focus on Hail City within the KSA brings specific climatic and geographical variables into play, such as adaptability to urban topography and the EVs' performance under local weather conditions.
2. **Data Collection and Technological Assumptions:** The reliance on survey data for insights into residents' attitudes may not capture the full spectrum of public opinion, especially among those less inclined toward digital surveys or less aware of EV technology. Furthermore, assumptions regarding the current state of solar technology, battery storage, and EV energy efficiency may not account for rapid advancements that could alter infrastructure needs and environmental impact assessments. The effect of dust accumulation on solar panels was not taken into consideration, especially since the region has little rainfall and is desert, which reduces the efficiency.
3. **Dynamic Urban and Policy Factors:** This study's static approach to urban development and policy frameworks may not fully reflect the dynamic nature of urban growth, demographic shifts, and evolving regulatory landscapes, which could influence the EV charging infrastructure demand and deployment strategies. The price of electric power also has an impact on the spread of EVs, and in return, raising the price of fossil fuels helps the spread of EVs.

6. Conclusions

This study included the design of a solar charging station network for EVs in urban areas of the KSA, with Hail City serving as a case study. Through the meticulous integration of survey results, parametric studies, and economic and environmental analyses, this study presents a compelling case for the strategic deployment of PV-EVCSs across Hail City.

In assessing the number of charging stations required, the research identified that Zone 4 would demand the highest number, totaling seven stations, without private charging options. This demand notably decreases with the introduction of a 60% rate of private charging, highlighting the significant impact of private EV charging solutions on public infrastructure needs. This study meticulously calculated the adjustments necessary to accommodate station maintenance and downtime, ensuring the robustness of the proposed network.

Parametric studies provided deep insights into the infrastructure requirements under varying conditions. For example, the impact of the average R on the number of stations needed illustrated that lower consumption rates could significantly reduce the number of required stations. Additionally, by exploring the scenarios across 17 zones in Hail City with standards such as a fixed average R of 0.20 kWh/km and BC set at 75 kWh, this study offers a nuanced understanding of the station distribution and capacity requirements.

The economic evaluation of the 1047.35 kWp PV system reveals an estimated conventional PBT of 11.69 years, accompanied by a return on assets of 10.17%. The system generates accumulated cash flows amounting to SR 7,169,294.62 over 30 years, while the estimated operational and maintenance expenses are predicted to be SR 50,000 per year. The overall investment cost for the solar PV and EV charging stations is SR 4,487,982. This cost is offset by yearly electricity savings from solar and grid sources, which can reach up to SR 396,465.26 by year 30.

The CO₂ savings for each EV were calculated using a rigorous generalization in the environmental study. These savings were estimated per km of driving. This methodology enabled a detailed assessment by considering the durations of the trips, which were obtained from a thorough investigation of the trip length (L), which was found to be approximately 77 km/day. The analysis was enhanced by considering the anticipated quantity of EVs. When using 80% PV energy, the emissions savings range from 3847 MtCO₂/year for 1000 vehicles to 192,349 MtCO₂/year for 50,000 vehicles, assuming a consumption rate of 0.15 kWh/km. The range of CO₂ emissions varies from 4917 MtCO₂/year for 1000 EVs

to 245,829 MtCO₂/year for 50,000 EVs, assuming a consumption rate of 0.30 kWh/km. Even with a lower PV integration rate of 20%, there were noticeable reductions in the CO₂ emissions. In conclusion, this work presents a detailed framework for the deployment of PV-EVCSs in Hail City, balancing technical, economic, and environmental considerations.

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Abbreviations

A (m ²)	Area	BC	Battery Capacity
CBC	Car Battery Consumption per Day	C	Total Number of Cars
ELDV	Electric Light-Duty Vehicle	Co (USD)	Equity Investment
EV	Electric Vehicle	Cn (USD)	Project's Cost in n Years
EVCS	Electric Vehicle Charging Station	d _{nominal} (%)	Nominal Discount Rate
GHG	Greenhouse Gas	d _{real} (%)	Real Discount Rate
KSA	Kingdom of Saudi Arabia	F	Total Number of Families
kWh	Kilowatt-Hours	G (W/m ²)	Solar Irradiance on the Module
LCOE	Levelized Cost of Energy	Gt (kWh/m ²)	Daily Average Global Radiation on the Slanted Surface
MtCO ₂	Megatons of Carbon Dioxide	L	Average Trip Length
NPV	Net Present Value	Lc (%)	Power Conditioning Losses
NS	Number of Stations	Lm (%)	Array Losses
NS'	Adjusted Number of Stations	M	Average Number of Family Members
ORS	Open Route Service	Nf	Fully Charged Number of Charging Cycles
PBT	Payback Time	O	Average Car Ownership per Family
PC	Private Charging	P	Total Population
PR	Performance Ratio	T	Average Conversion Percentage to EVs
PV	Photovoltaics	Ta	Mean Ambient Temperature
PVE	PV System Efficiency	Tc	Cell Temperature
PV-EVCSs	Photovoltaic Electric Vehicle Charging Stations		
R	Consumption Rate		
RE	Renewable Energy	η _{Inverter} (decimal)	Efficiency of the Inverter
ROA	Return on Assets	η _e (%)	Array's Average Efficiency
SC	Station Capacity	η _R (%)	Module Efficiency at Reference Temperature (TR)
SD	Station Capacity per Day	μ	Temperature Coefficient
SR	Saudi Riyals (1 USD ≈ 3.77 SR)		
US	United States		

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