Demand and Sustainability Analysis for A Level-3 Charging Station on the U.S. Highway Based on Actual Smart Meter Data

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***Abstract*—Over the next five years, the U.S. will deploy DC fast charging stations along its interstate highway system under the National Electric Vehicle Infrastructure (NEVI) formula program. The large-scale deployment of NEVI charging stations will significantly increase charging demand, posing challenges to power systems. Thus, understanding the charging demand characteristics of existing NEVI-compliant stations is crucial. However, limited access to smart meter data and few compliant stations make existing studies insufficient for NEVI research. This article presents a thorough analysis of an existing NEVI-compliant Level-3 DC charging station's power demand, located on the U.S. interstate highway in the Northern High Plains. The real 15-minute smart meter data was examined to evaluate the station's power consumption and demand characteristics across various time intervals and holidays. The station's unique location enables accurate representation of EV charging patterns for highway travel in the northern high plains throughout the year. Additionally, the study investigates the station's sustainability by assessing local solar generation potential and offers preliminary results for the future carbon market. This research provides a detailed guide on examining EV charging station power demand and consumption characteristics on the U.S. interstate highway using smart meter data, ultimately assisting the power industry in facilitating the NEVI formula program deployment.**

***Index Terms*—AMI data, data analysis, DC charging, EV charging, highway, level-3 charging, NEVI, RES, sustainability.**

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I. Introduction

IN THE U.S., interstate highways play a critical role in the national transportation system in terms of economic sustainability, national defense, and natural disaster evacuations [1]. As shown in Fig. 1, the interstate highways connect all 48 states together in the U.S. mainland, which is considered one of the safest road networks in the world [1]. Meanwhile, with the rapid growth of Electric Vehicles (EVs), EV charging infrastructures have been installed largely shown in Fig. 2. In February 2022, the U.S. Departments of Transportation and Energy announced the new National Electric Vehicles Infrastructure (NEVI) Formula Program, which will provide $5 billion over five years to create an EV charging network along the interstate highway system nationally [3]. Many studies have shown that EV charging will create considerable pressure and challenges for power grids especially power distribution systems [4], [5], [8], [29]. The new NEVI Formula Program will further increase the power demand and bring a considerable burden to power distribution systems, which could jeopardize the reliability and stability of power grids without fully understanding the characteristics of current EV charging power demand on the U.S. interstate highways.

Currently, different EV charging mechanisms developed and conducted extensively in the existing literature to address the EV charging challenges on power grids [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. In article [4], authors proposed a framework to coordinate EV charging and DER generation, addressing challenges and benefiting EV owners and DER investors. Paper [5] discusses the impact of EV charging and strategies to reduce peak demand. Caltech researchers developed an adaptive charging network and a scheduling algorithm for smart charging [6], followed by an open-source simulator for data-driven research [[7]. Paper [8] studies peak charging demand on distribution systems with fast charging on highways. Paper [9] presents a simulation-based study analyzing charging capacity between two Mexican cities. Paper [10] analyzes long-term EV charging demand on an Arizona highway using geospatial data. Paper [11] provides a qualitative analysis of large power demand from future EV charging. In article [12], a TOU schedule is developed for EV charging benefiting utilities and customers. Paper [13] uses a simulation model to evaluate highway charging infrastructure, while paper [14] proposes a dynamic pricing

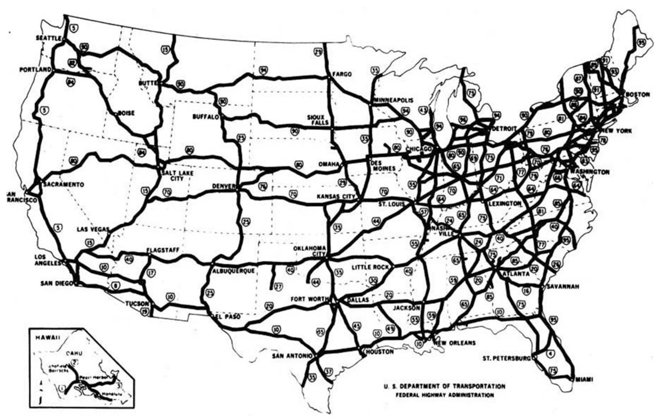

Fig. 1. The U.S. interstate highway system [1].

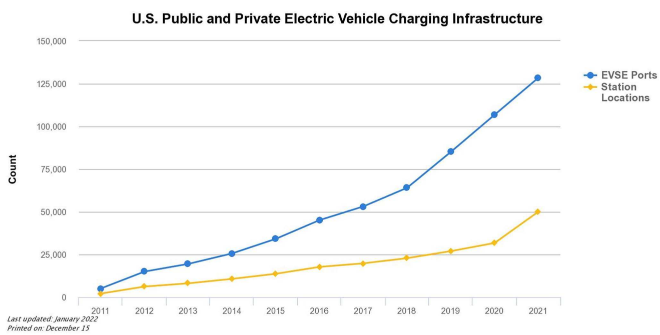

Fig. 2. The U.S. EV charging infrastructure trend [2].

methodology for EV charging stations to encourage renewable energy consumption. Paper [15] optimizes highway charging stations considering renewable power in China, and paper [16] develops machine learning models to predict EV taxi operations, offering optimized charging strategies. Paper [17] proposes a multi-objective optimization framework for battery energy storage systems, and paper [18] forecasts day-ahead EV charging demand using Dundee, Scotland data. Paper [19] develops a real-time smart charging algorithm, and paper [20] creates smart charging schedules for highway-traveling EVs.

On the other hand, the EV charging sustainability has also been investigated in multiple studies. According to the Federal Highway Administration, the average annual miles per driver in the U.S. is about 13000, requiring roughly 4000 kWh of electricity for an EV [21], [22]. Proper utilization of renewable energy is crucial for sustainable EV charging infrastructure. Various studies explore renewable energy for EV charging. Papers [23], [24], [25], [26] demonstrate solar energy for charging EVs at workplaces, shuttle buses, and industrial microgrids. Papers [25], [27] propose charging control strategies considering photovoltaic (PV) generation to reduce costs. Paper [28] develops an EV demand forecasting method considering PV systems. Paper [29] studies challenges of solar-powered EV charging in a U.K. city, and paper [30] explores PV system configurations for efficient space utilization. Paper [31] presents a simulation for a bidirectional solar PV-assisted EV charging station.

However, due to the lack of availability of actual highway electrical vehicles fast charging data, the researchers have either employed simulation-based techniques [8] or conducted travel surveys [20] to characterize EV charging demand on highways. Addressing this research gap is crucial for future power system operations, considering the increasing number of EVs and the upcoming NEVI formula program in the U.S. This article studies a level-3 DC fast charging station on a U.S. interstate highway using actual high-resolution advanced metering infrastructure (AMI) data. The main contributions of this article are summarized as follows:

1) This research paper is the first study to utilize actual 15-minute smart meter data to showcase the charging demand characteristics of a level-3 NEVI-compliant charging station on the U.S. interstate highway.
2) This research study presents a fundamental procedure for analyzing NEVI-compliant EV charging demand characteristics using AMI data, thereby contributing valuable insights to the scientific literature.
3) This study quantifies the sustainability of a NEVI-compliant EV charging station by evaluating a local renewable energy resource and greenhouse gas emission reduction.

The outcomes of this study hold implications for professionals in the power industry and research institutions, as it offers valuable insights into the power demand and sustainability of a NEVI-compliant Level-3 EV charging station in sparsely populated rural areas on the U.S. interstate highway system. The rest of the paper is structured as follows. Section II presents the analysis procedures and charging demand characteristics based on AMI data. Section III quantifies the uncertainties of charging load profiles. Section IV analyzes the sustainability of the EV charging station, and the conclusion of the study is presented in Section V.

II. Analysis Procedure Using AMI Data

A. *Uniqueness of The Charging Station*

This study highlights the significance of the Level-3 NEVI-compliant charging station, located strategically along a primary interstate highway traversing the Northern High Plains, in close proximity to numerous renowned National Parks and prominent tourist attractions within the United States. As shown in Fig. 3, which presents a map of the DC charging stations in the region, the charging station in this study is the only NEVI-compliant charging station in the area. The importance of this charging station's location is emphasized, as it provides a critical charging infrastructure for EV travelers in sparsely populated rural areas. The findings of this study provide valuable insights into the power demand and sustainability of this charging station, aiding professionals in the power industry in better understanding the charging demand characteristics and facilitating the NEVI formula program implementation in the Norther High Plains of the U.S.

The charging station under investigation is equipped with eight charging ports, each capable of delivering up to 150 kW of power. Located in a rural town with a population of fewer

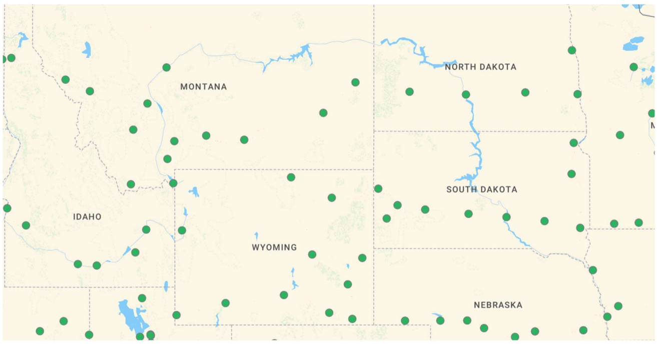

Fig. 3. DC charging stations in Northern High Plains [32].

than 900 residents, the impact of the charging station on local power consumption remains minimal. The site experiences four distinct seasons, with average monthly temperatures varying from 17 °F to 87 °F. Consequently, this charging station serves as an appropriate case study for analyzing power demand at Level 3 electric vehicle (EV) charging stations situated along U.S. interstate highways characterized by seasonal variations. The interstate is a popular route for tourists during the summer months, which further supports the relevance of this charging station as a representative model of Midwestern EV charging patterns for travelers. Therefore, this charging station can be considered as an ideal representative of NEVI formula charging stations in Northern High Plains of the US and accurately characterize highway charging demand.

This article analyzes 15-minute smart meter data of a level-3480-volt fast charging station for the year 2021. To illustrate the charging patterns, both charging power consumption in kWh and charging power demand in kW are shown in this article. With this data, patterns can be analyzed for months, weekdays, seasons, and holidays in order to gain a better understanding of the behaviors of interstate charging stations in the region.

B. Monthly Charging Patterns

To gain insight into the charging power consumption trends of the NEVI-compliant charging station over the duration of a year, an analysis of the average daily power consumption for each month is conducted and presented in Fig. 4. The investigation revealed that the maximum EV charging consumption peak was recorded in July, with an average daily power consumption of 660 kWh. In contrast, February exhibited the lowest average daily power consumption, with a daily consumption of 121.6 kWh.

C. The Peak and Valley Charging Demand

In order to demonstrate the charging behavior trends during a high-consumption period, the charging power demand for the month of July was analyzed using 15-minute AMI data. Fig. 5 displays the average power demand over each 15-minute interval throughout the month. The analysis indicates that the typical daily demand follows a bell curve pattern, with demand increasing from 8 AM and peaking at approximately 1:30 PM

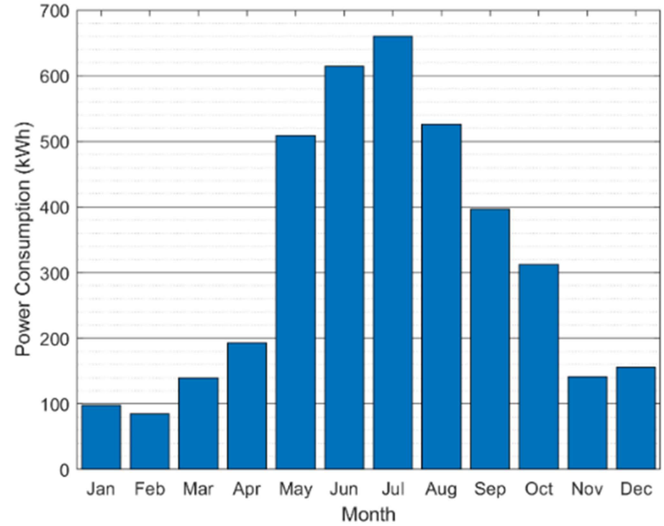

Fig. 4. The average daily demand in each month.

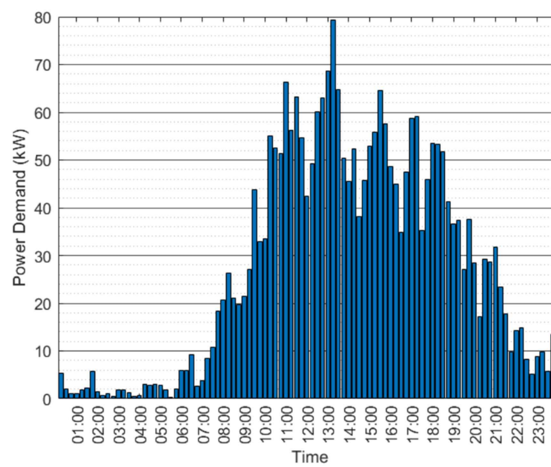

Fig. 5. Average 15-minute demand in July (highest).

before tapering off by 10 PM. The highest average demand in July, which was nearly 80 kW, occurred at approximately 1 PM.

The observed charging demand pattern corresponds with the sunrise and sunset patterns in the region during that season. In July, the sunrise occurs around 5:30 AM, while the sunset takes place around 8:30 PM. The study indicates a two-hour lag between the sunrise and the increase in charging demand, as well as a similar two-hour delay between the sunset and the demand tapering off. These results demonstrate a significant correlation between the driving behavior of summer travelers and the patterns of EV charging demand.

In order to compare the characteristics of the highest and lowest power demand, the study also examined the charging behavior during the lowest demand month. Fig. 6 illustrates the average hourly power demand at the charging station in February 2021. The analysis reveals that there is no discernible or distinctive pattern for charging demand during this low-demand period. Demand peaks occur several times each day and drop to below-average levels after each peak. The two highest peak

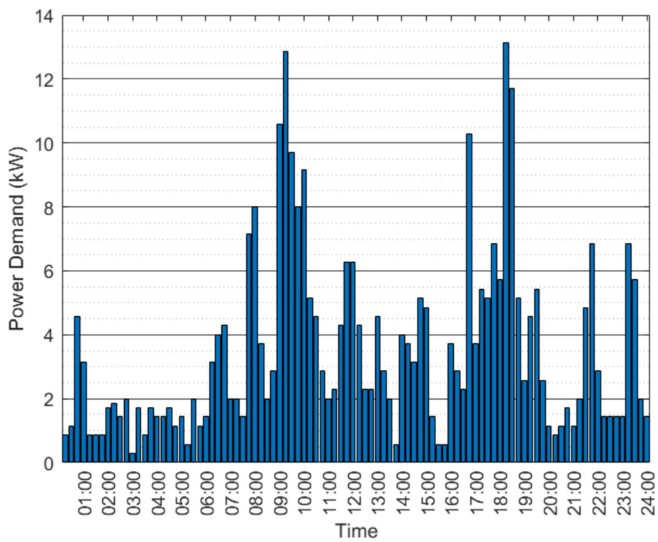

Fig. 6. Average 15-minute demand in February (lowest).

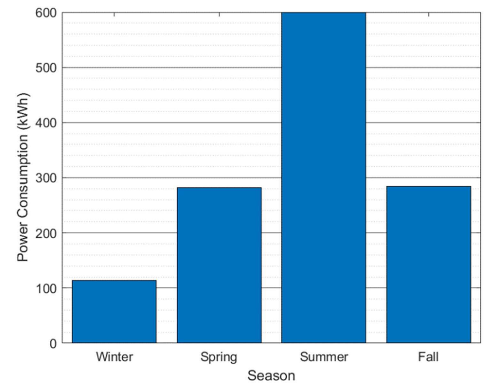

Fig. 7. Average daily power consumption of the charging station in each season.

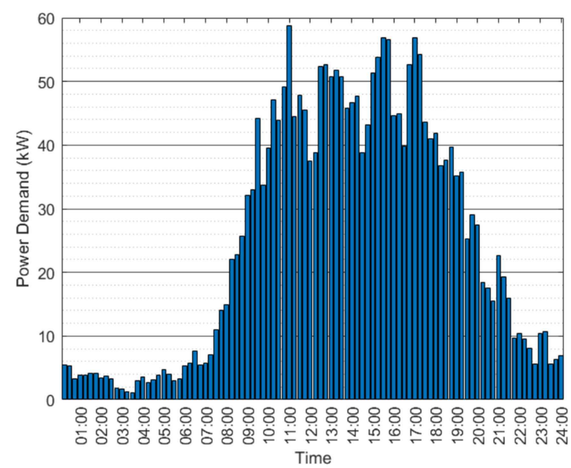

Fig. 8. Average hourly demand in the summer.

demands, both at 13 kW, occur at 9:30 AM and 6:30 PM, which may suggest a correlation between winter travelers' charging behavior and typical workday start (9 AM) and end (5 PM) times. Another notable trend is the demand spikes that occur at roughly one-hour intervals from 6 AM to 1 AM, suggesting a possible correlation between travelers' charging patterns and regular hourly intervals.

Figs. 5 and 6 depict notable disparities in the charging behavior of EV owners during winter and summer months, respectively, for highway travel. The data analysis indicates that the summer month of July exhibits a considerably higher and more uniform charging demand compared to the winter month of February. This finding has significant implications for system operators and utility companies, as it underscores the importance of incorporating seasonal demand patterns into load forecasting models, particularly with the increasing deployment of EV charging infrastructure along highways.

D. Summer and Winter Charging Power Consumptions

The findings from the preceding subsections provide clear evidence that level-3 charging demand on interstate highways is significantly influenced by seasonal variations. The power consumption and demand patterns during summer and winter months differ significantly from one another. To further elucidate the seasonal impact of charging stations on power grids, this section presents a comparison of summer and winter charging power consumption and demand. The winter period is defined as December, January, and February, taking into account the local temperature, while the summer season includes June, July, and August. The remaining months are categorized as shoulder seasons (spring and fall). Fig. 7 illustrates the average daily power consumption of the charging station during each season. Notably, summer exhibits the highest average daily power consumption, with 600 kWh, while both spring and fall have comparable average power consumptions of 280 kWh. In contrast, winter has the lowest average demand, at 113.8 kWh, which is approximately five times lower than the peak demand in summer.

In order to gain insights into the summer charging demand, this study examined the average daily demand during summer, as illustrated in Fig. 8. The results indicate that the charging demand during summer rises from 8 AM and peaks at 2 PM, before settling around 10 PM. Of note, the largest average peak demand occurs at 11 AM, with additional spikes observed at 1 PM, 3:30 PM, and 5 PM. These observations suggest that the charging behavior of most summer EV travelers follows a regular 2-hour charging interval during peak travel times.

In contrast, the study also analyzed the winter demand and depicted the results in Fig. 9. The 15-minute charging demand during winter exhibits a small bell curve pattern, with half-hour spikes occurring at the top of every hour from 6 AM to 11 PM. This pattern is more consistent than that observed in February but occurs over a smaller time period. The monthly and seasonal analyses suggest that during summer months, the charging demand follows a large bell curve pattern starting in the early morning and tapering off in the late evening, while winter months exhibit a smaller, more sporadic demand, with spikes occurring regularly in half-hour to hour intervals except during the late evening and early morning. These seasonal patterns are critical

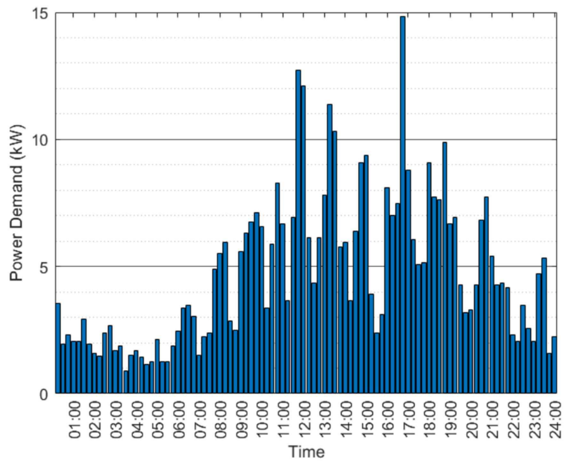

Fig. 9. Average 15-minute demand in the winter.

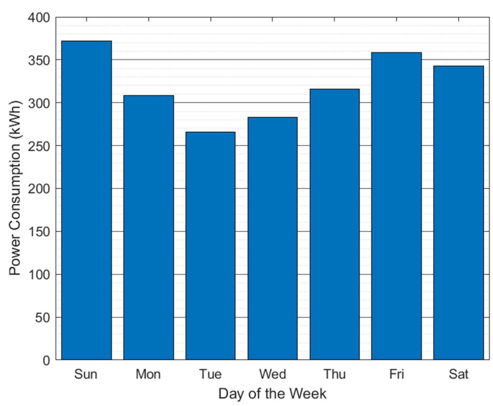

Fig. 10. Average daily power consumption of weekdays and weekends in 2021.

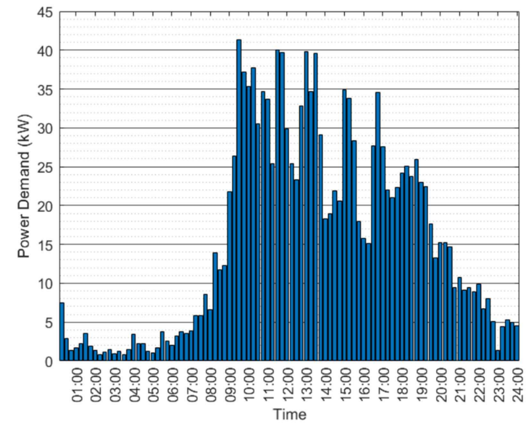

Fig. 11. Average 15-minute charging demand on Sundays.

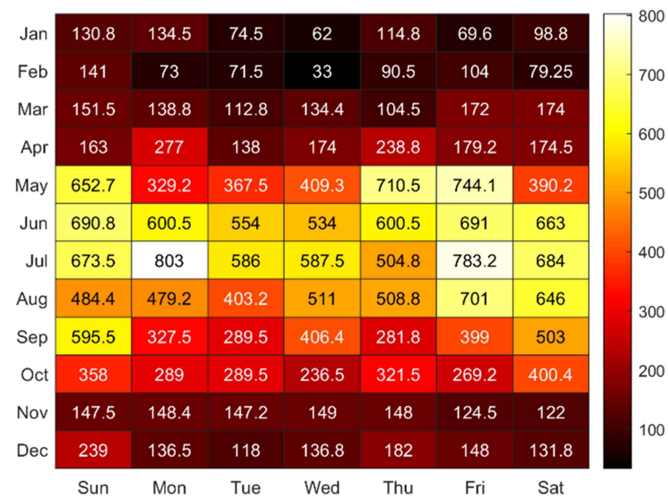

Fig. 12. Heatmap of average daily charging demand (kW) for weekdays and weekends per month.

for power system operators to consider when conducting load forecasting and electricity market participation. Different strategies and updated models must be explored with the increasing deployment of EV charging infrastructure.

E. Weekdays and Weekends Power Consumptions

This section presents an analysis of the average daily charging power consumptions on weekdays and weekends throughout the year, as depicted in Fig. 10 and Table II. The results indicate that the average peak consumption occurred on Sundays, reaching 371.8 kWh, while Tuesdays exhibited the lowest charging consumption of 265.8 kWh. Notably, Fridays and weekends exhibited the largest charging consumption, whereas Tuesdays and Wednesdays had the lowest charging consumption. This finding suggests that more EV owners tend to travel on interstate highways from Friday to Monday, with less highway travel in the middle of the week.

To further investigate the highest charging demand day (Sunday), this study examined the average 15-minute demand on Sundays in 2021, as illustrated in Fig. 11. The analysis reveals a rapid increase in demand with a rise time of less than an hour, from 8 AM to 9 AM. The subsequent trend shows a steadily decreasing linear slope with spikes occurring approximately every two hours. This two-hour charging interval aligns with the previously observed power demand patterns.

F. Average Daily Power Consumptions in Weekly View

This subsection presents an analysis of the average daily charging consumption in a weekly view for different months and seasons, using two heat maps to better illustrate the power consumption patterns of weeks, months, and seasons. The results, as depicted in Figs. 12 and 13, reveal a significant seasonal impact on daily charging power consumption. Such a drastic difference in charging consumption would require sufficient operational flexibility for power grids, particularly with the increasing deployment of EV charging infrastructure. Furthermore, different charging rates, such as Time-of-Use (ToU) and seasonal tariff strategies, should also be taken into account for future charging stations on the U.S. highway systems.

G. Holidays Charging Demand in Different Seasons

As previously discussed, the seasonal impact on EV charging stations is significant. This subsection investigates the

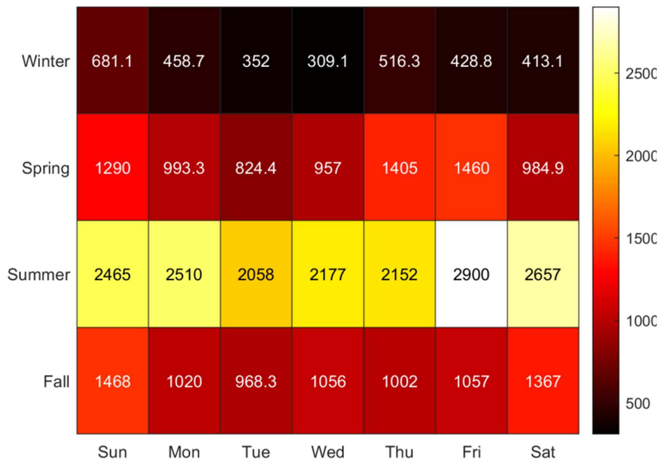

Fig. 13. Heatmap of average daily charging demand (kW) for weekdays and weekends in each season.

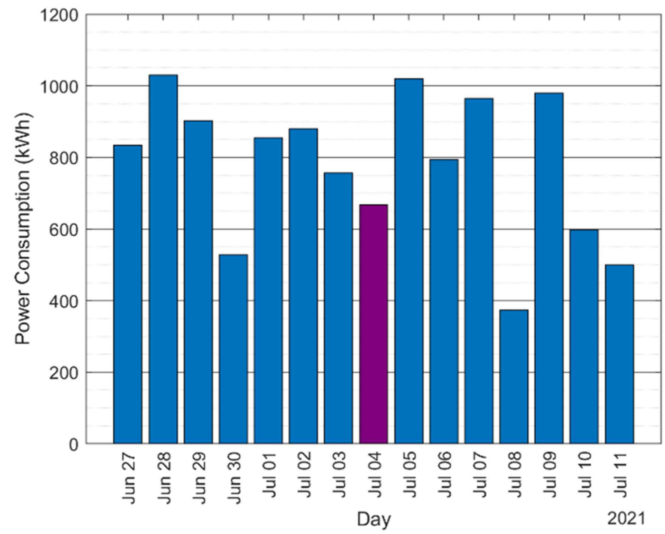

Fig. 14. Average daily charging consumption before and after July 4th (summer holiday).

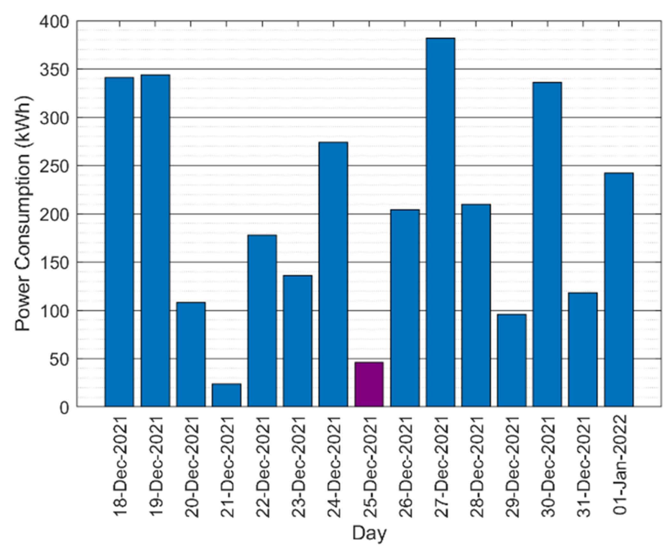

Fig. 15. Average daily charging consumption before and after Christmas (winter holiday).

correlation between charging power consumption patterns and holidays in the U.S. during different seasons, including New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, and Christmas Day. Given the traveling patterns for these holidays, two peak demand days are found for each holiday, a few days before and after the holiday. It shows that most travelers tend to leave on weekends and the Monday following the holidays, with no outliers. For holidays that fall towards the weekend, travelers typically leave on Sundays before returning to work on Monday. The 4th of July and Christmas present outliers to this pattern. The 4th of July falling on a Sunday may lead to travelers taking the following day off. For Christmas, the Monday following the holiday was the peak traveling day. Family-oriented holidays may lead to travelers spending extra days after the holiday with their families, leading to lower demand. The most considerable difference between the post-holiday peak and the holiday is Labor Day, with a six-day difference.

To further investigate the charging demand characteristics during summer, winter, and shoulder seasons, the power demand for three major holidays in each season was plotted in Figs. 14, 15, and 16. Each holiday's daily demand is highlighted in purple. Fig. 14 shows the average daily power consumption for a week before and after Independence Day, which exhibits a relatively steady charging consumption pattern before and after the holiday. Since July is a peak charging demand month, the holiday in July does not have a significant impact on charging patterns. Fig. 15 shows the average daily consumption before and after Christmas, demonstrating that Christmas has a noticeable impact on the charging consumption patterns of the Level-3 charging station on the interstate highway. The two major pre-Christmas peak days occur around a week before Christmas, and Christmas Eve also has high charging consumption. For post-Christmas peak days, the two large peak travel days after Christmas could be the result of travelers leaving from Christmas and traveling to their New Year's destinations. However, the difference in charging consumption between Christmas day, pre-Christmas, and post-Christmas days is significant, unlike the holiday (Independence Day) in summer. Fig. 16 shows the average daily charging consumption a week before and after Labor Day, where average daily charging consumption remains consistent with prominent pre and post-charging peaks. Unlike summer and winter holidays, the shoulder season holiday has a relatively noticeable impact on charging patterns on the interstate highway.

The analysis reveals that EV charging demand for holidays is significantly dependent on the season. Specifically, during summer, the charging patterns exhibit relative stability before and after holidays. However, during the winter season, the charging demand is noticeably impacted by holidays. Furthermore, while the shoulder season holiday impact is not as significant as

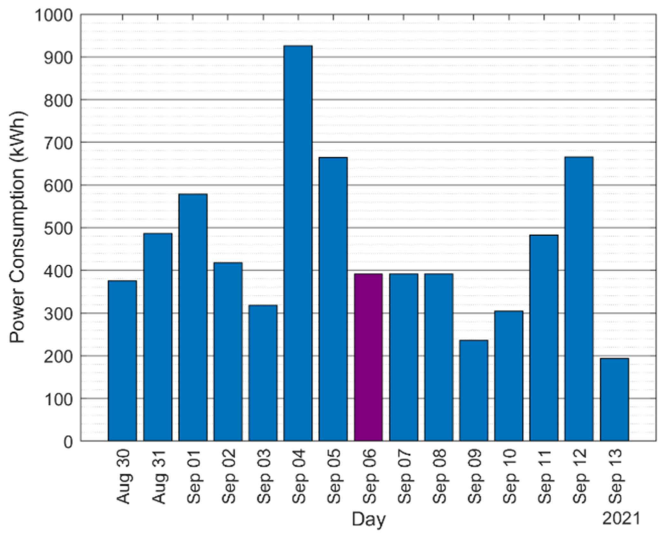

Fig. 16. Average daily charging consumption before and after Labor Day (shoulder season holiday).

the summer holiday, it is still more noticeable than the winter holiday.

H. Load Factor Analysis

From the electric utility standpoint, the efficiency of the charging stations on highways is critical for capital investments. Load factor gives an indication of how well the utility's facilities are being utilized [33]. From the utility's standpoint, the optimal load factor would be 1.00, because the system has to be designed to handle the maximum demand. Load factor is defined as the average power over a period as a fraction of the peak (or rated) power of the equipment [34]. Since the load factor is a vital metric in power systems to assess system efficiency, optimize infrastructure planning, manage energy demand, reduce costs, and minimize environmental impact, this study provides a daily load factor using 15-minute resolution data for this NEVI-compliant charging station. For a time-varying load power $p(t)$, load factor over any specific operating period T, is given by [34]:

$$LF \quad (\%) = \frac{Average\ kW\ load}{Peak\ kW\ load} \times 100\%$$

$$= \frac{\frac{1}{T}\int_0^T P(t)\,dt}{Peak\ kW\ load} \times 100\%$$

Fig. 17 illustrates the daily load factor for a charging station throughout the year 2021. It is evident from the data that the charging station situated on the highway experiences a notable surge in load factor during the summer months. This increase can be attributed to factors such as heightened travel and tourism activities, longer daylight hours, and favorable local weather conditions, which contribute to a higher load factor for electric vehicle charging infrastructure. Therefore, utility companies could consider different incentive charging programs to enhance the load factor of NEVI-compliant charging station in the future.

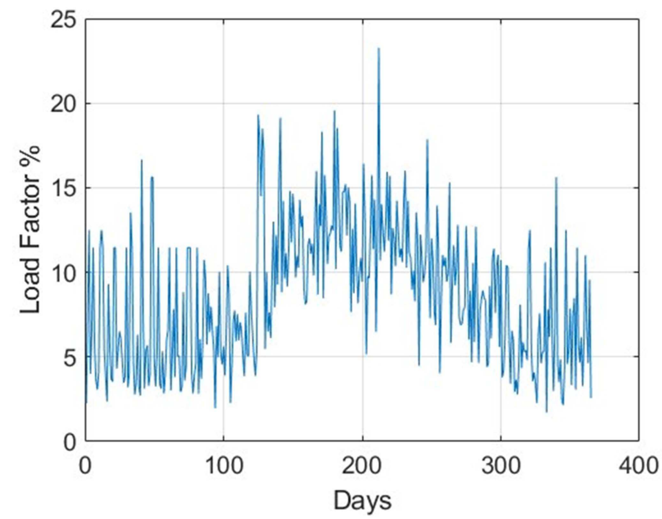

Fig. 17. Daily load factor of 2021.

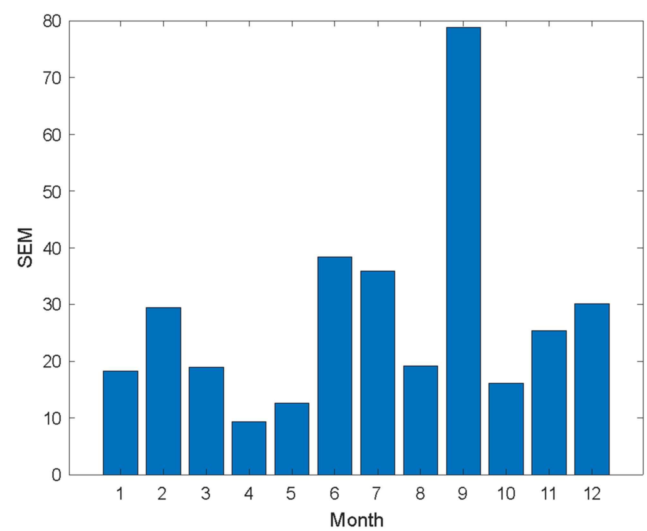

Fig. 18. *SEM* of daily charging consumption in each month.

III. Quantification of Uncertainty

Uncertainty quantification (*UQ*) is the process of identifying, characterizing, and quantifying uncertainties in a real-world system. The primary goal of *UQ* is to provide accurate and reliable estimates by considering the uncertainties associated with various factors, such as model structure and measurement errors. In this article, the *Standard Error Mean* (*SEM*) is adopted to quantify the uncertainty of the daily charging consumption of each month and average daily charging demand. The *SEM* is defined as:

$$SEM = \sigma/\sqrt{n} \tag{1}$$

where σ represents the sample standard deviation and *n* is the sample size.

In this article, *SEM* for the daily charging consumption of each month in 2021 is calculated and plotted in Fig. 18. As shown, September has significant higher *SEM*. It indicates that the daily charging consumption of September has high variability, the

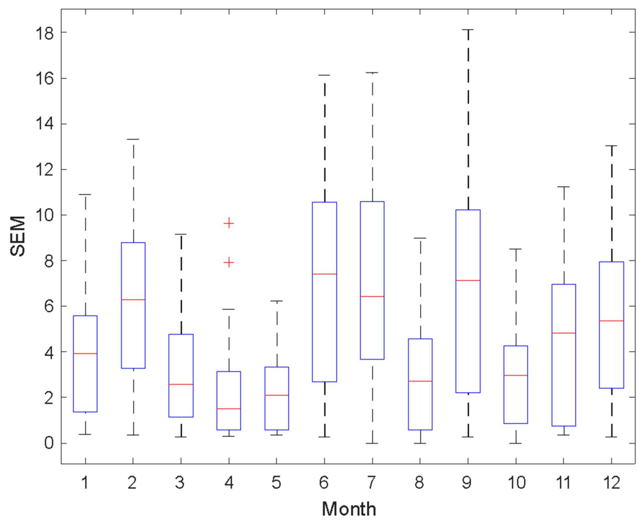

Fig. 19. Boxplots for SEM of 15-min daily charging demand in each month.

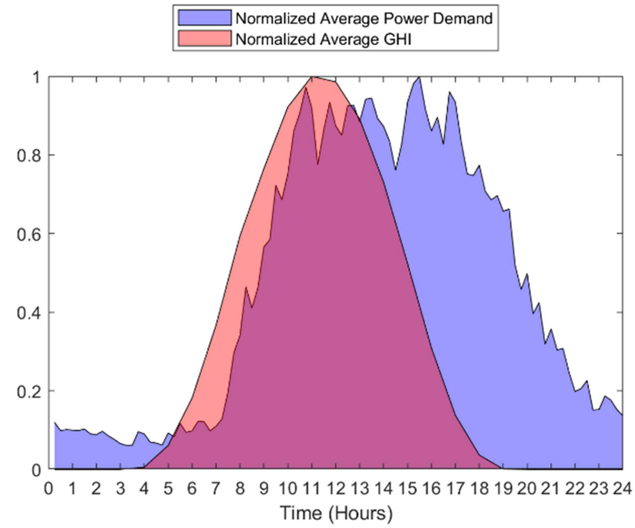

Fig. 20. Normalized daily charging demand and GHI.

15-minute datasets are more spread out. This is mainly because September is a transition period between peak traveling season (warm months) and off-peak traveling season (cold months) that has diverse EV charging patterns. Therefore, the load profile of the charging station in September can be much more challenging to model and forecast.

To clearly show the daily charging demand uncertainty in each month, the boxplot of *SEM* is applied and shown in Fig. 19. A boxplot, also known as a box-and-whisker plot, is a graphical representation of a dataset that provides a visual summary of its central tendency, dispersion, and possible outliers. The box represents the interquartile range (IQR), which contains the middle 50% of the data. The IQR is the range between the first quartile (Q1) and the third quartile (Q3). The red line in the blue box indicates the median values of *SME* of daily charging demand in each month, which divides the box into two parts. The bottom and top parts are, respectively, the first quartiles and the third quartiles. The lines extending from the box are called whiskers. Whiskers represent minimum and maximum *SEM* values of average charging demand. The red cross signs in April are considered as outliers due to abnormal charging demand. Distinctive from the rest of summer months, August has much smaller *SEM*, it implies that the charging demand patterns in August has similar patterns. Besides, the charging demand patterns during shoulder months (April, May and October) are relatively stable. However, due to extremely low charging consumption, *SEM* during winter months is also relatively high. This result illustrates that June, July and September has much more volatile power demand. Therefore, the analysis reveals that the uncertainties of the charging demand and consumption on the highway in the Northern High Plains are significantly dependent on the season. Consequently, local utility companies must consider different load models for NEVI-compliant EV charging stations in the future. Additionally, implementing different tariffs and demand response programs could minimize the charging demand uncertainty.

IV. Sustainability Analysis

Utilizing renewable energy for EV charging is crucial for both decarbonization and power system operation. With the increasing adoption of EVs, the power grid must have sufficient capacity and flexibility to meet the rising demand for EV charging. This is essential to ensure the sustainability of the large-scale implementation of EV charging infrastructure on the U.S. highway system. According to the National Environmental Policy Act, sustainability involves creating and maintaining conditions in which humans and nature can coexist in productive harmony for present and future generations [35]. Sustainability aims to improve the quality of life by taking into account environmental, social, and economic factors [36].

A. Solar Generation Potential

According to recent research findings [37], the solar capacity in the United States is anticipated to undergo a tripling within the next five years, which suggests that solar photovoltaic (PV) represents a promising energy resource for ensuring the sustainability of electric vehicle (EV) charging stations situated on highways. In this section, we conduct an assessment of the sustainability of a level-3 EV charging station powered by solar PV generation, based on the local Global Horizontal Irradiance (GHI) [38]. In addition, we present a worst-case scenario to serve as a case study for the sustainability analysis. Fig. 20 depicts the normalized local average daily GHI across a year, as well as the normalized average daily charging demand of the year 2021. The overlapping percentage amounts to 57%. These findings indicate that the charging power demand of the level-3 EV charging station situated on the U.S. interstate highway aligns well with the nature of solar generation.

B. Sustainability Case Study

To assess the feasibility of utilizing solar PV for highway EV charging stations, this study employs a renewable simulation

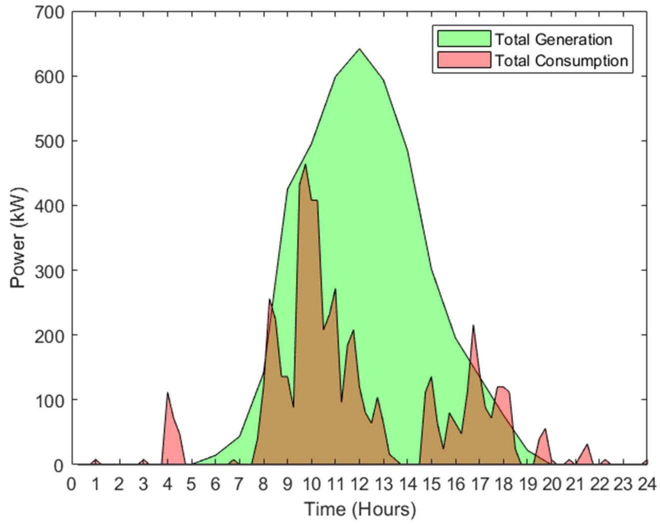

Fig. 21. The charging demand curve and solar generation curve on May 23rd, 2021.

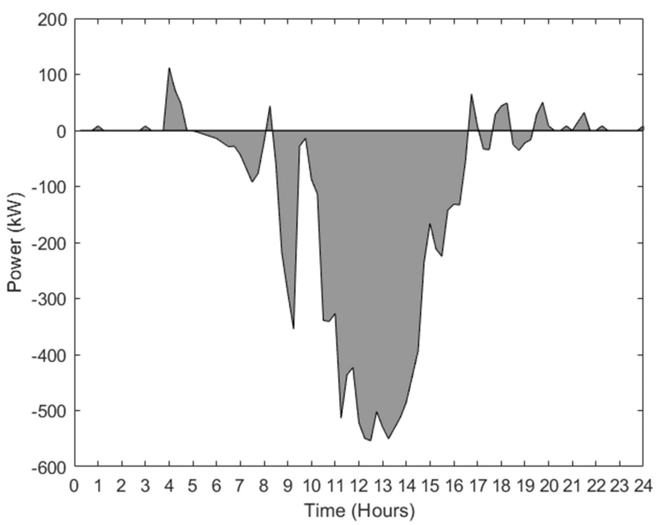

Fig. 22. The difference between charging demand and PV generation supply on May 23rd, 2021.

tool [39] to simulate the solar PV generation at the charging station location. The worst-case scenario, defined as the highest charging demand peak of the year, is considered in the analysis. A solar PV capacity of 800 kW is assumed to be sufficient to cover the peak charging demand of the year 2021. The peak demand of 464 kW occurred on May 20th, 2021, at 2:45 PM, and on May 23rd, 2021, at 9:45 AM, and the latter is considered as the worst-case scenario since the peak occurs in the morning. The objective of this assumption is to ensure that the peak charging demand can be met by solar generation during daylight hours. Fig. 21 displays the solar generation curve of an 800 kW PV system and charging demand, while Fig. 22 shows the negative excess generation and positive excess consumption.

To quantify the sustainability of the charging station using PV generation for the worst-case scenario, two new indexes, *Solar Efficiency* (*SE*) and *Charging Coverage* (*CC*), are defined

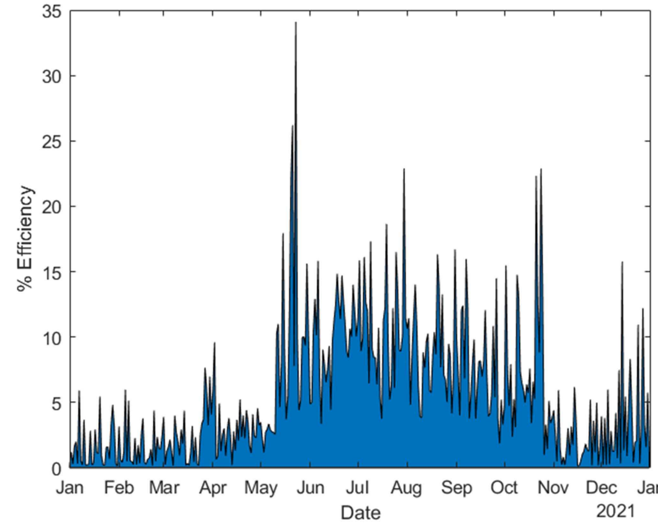

Fig. 23. The local *Solar Efficiency (SE)* of the year.

from two different perspectives in this article. The *SE* implies how much energy generated by the PV system can be absorbed directly by the EV charging station without an additional energy storage system or feeding back to the power grid. The *CC* indicates how much EV charging demand can be supplied by the PV system.

The *SE* is the percentage of the total generation from the integrated PV system that is being consumed by the EV charging station, shown in (2)

$$SE = \frac{TG - EG}{TG} \times 100\% \tag{2}$$

where *TG* (kWh) represents the total generation of the solar system, and *EG* (kWh) is the excess generation of the PV system.

The *CC* is the percentage of the total power consumption of the EV charging station that can be covered (supplied) by the PV generation, which is defined in (3).

$$CC = \frac{TC - EC}{TC} \times 100\% \tag{3}$$

where *TC* (kWh) is total charging power consumption, and *EC* (kWh) is excess charging power consumption.

The analysis depicted in Fig. 18 indicates that there is an abundance of excess solar generation during the middle of the day when the charging demand is low. In the absence of sunlight, the charging consumption draws electricity from the grid. The *SE* and *CC* for the peak demand day were computed as 34.1% and 89.8%, respectively. This suggests that nearly 90% of the EV charging power consumption was met by PV generation, while only 10% was derived from the grid. Moreover, 34% of the PV generation was allocated to the EV charging station, while the remaining 66% was fed back into the power grid.

The *SE* and *CC* of an 800 kW PV system in 2021 are illustrated in Fig. 23 and 24. As shown in Fig. 23, the SE experiences a minor increase during the summer months, although it remains relatively low throughout the year. This outcome highlights the likelihood of wasted solar-generated electricity in the absence

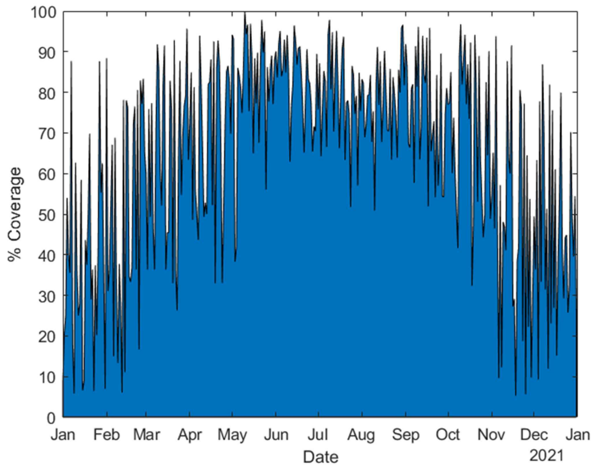

Fig. 24. The local *Charging Coverage (CC)* of the year.

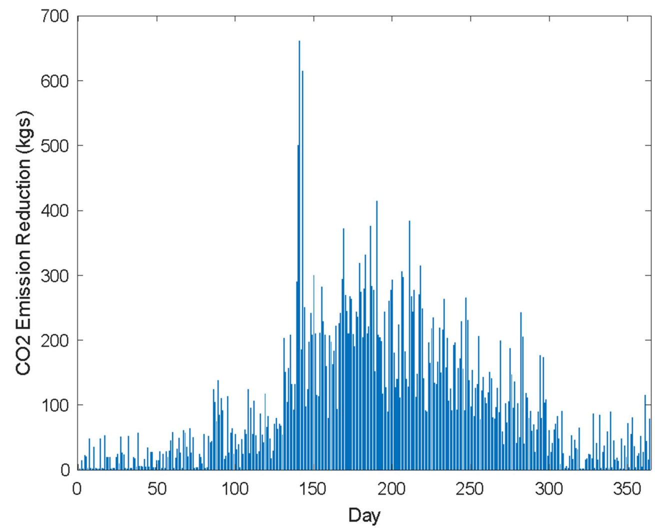

Fig. 25. Daily CO2 emission reduction based on 800 kW PV.

of a battery energy storage system (BESS) or feedback to power grids. As such, the integration of PV into highway charging stations requires additional costs for BESS and control devices. Fig. 21 depicts the *CC* in 2021, which is found to be significantly higher throughout the year than the *SE*. This finding implies that local solar generation can adequately meet the EV charging demand on the highway, particularly during the summer months. As a result, the PV system can be viewed as a viable solution for enhancing the sustainability of EV charging on highway systems.

The analysis depicted in Fig. 23 and 24 reveals that relying solely on solar PV systems to sustain EV charging stations on the interstate highway is an inefficient approach. Furthermore, the study indicates that constructing a solar PV system solely for the worst-case scenario is not cost-effective. These findings are significant since they demonstrate the need to explore alternative solutions such as battery energy storage systems or integrating the PV system with the grid to improve the efficiency and cost-effectiveness of EV charging on the highway system.

C. CO2 Emission Reduction and Carbon Market Potential

To further assess the environmental impact of the electric vehicle (EV) charging station, we will consider its sustainability based on local solar generation capacity and carbon dioxide (CO2) emissions reduction using *CC* found previously. The charging energy provided by the solar system can be determined using the CC results depicted in Fig. 24. As per the United States Environmental Protection Agency, each kilowatt-hour (kWh) of electricity is associated with 0.433 kg of CO2 emissions. Fig. 25 illustrates the annual CO2 emissions reduction in kilograms. Throughout the year, the total CO2 emissions reduction amounts to approximately 41.6 tons. This is comparable to the carbon sequestration achieved by growing 624 tree seedlings for a decade and preserving 45 acres of U.S. forests for one year.

As the world strives towards decarbonization goals, the carbon market will play a vital role in the energy sector. The carbon market aims to decrease greenhouse gas emissions, mainly CO2, by assigning a price to emissions and enabling companies to trade carbon allowances or credits. This market-based approach encourages businesses to reduce emissions cost-effectively. With the upcoming NEVI formula program, this EV charging business could be significant and act as an important participant in the carbon market. The result of this study shows that renewable energy can play a crucial role in supporting EV charging stations and utility companies in the future carbon market. By integrating renewable energy sources into their operations, these entities can significantly reduce greenhouse gas emissions and contribute to global decarbonization goals. Utilizing renewable energy not only lowers emissions but also generates cost savings through the sale of excess carbon credits or allowances in the carbon market. As the demand for clean electricity increases with the growth of EV adoption, further investments in renewable energy projects will be driven, fostering the clean energy transition in the power sector.

V. Conclusion and Future Work

This article analyzes a current NEVI-compliant DC fast charging station in Northern High Plains of the U.S. The characteristics of charging demand and consumption patterns are investigated using 15-minute AMI data. Besides, the sustainability of the charging station is also assessed based on the local solar generation potential. The result shows that the charging patterns of the DC charging station on the interstate highway within the sparsely populated rural area are heavily season and time dependent, and solar PV can be well utilized for this EV charging stations, and similar configuration for EV charging stations have huge potential in the carbon market. However, energy storage systems should be considered to improve energy and economic efficiency to ensure the sustainability of EV charging stations using PV systems. This is the first study using actual AMI data from a NEVI-compliant level-3 charging station on a major U.S. interstate highway within a rural area to show the changing patterns. This article can serve as a foundation for the power engineering community to provide a general understanding on

NEVI charging station characteristic in Northern High Plains, which will also facilitate the NEVI formula program implementation in the U.S. Besides, the result of this study can be used for highway charging station operation modeling, optimization, and forecasting.

In the future work, the load forecasting and charging behavior models will be developed using AMI data of multiple years. In addition, the correlations between traffic patterns and EV charging demand patterns should be also investigated for effective NEVI charging station allocations.

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