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Original Article

Optimal Planning of Hybrid Renewable Energy-Based Charging Infrastructure Under Varying Grid Outage and Scaled Electric Vehicle Sessions

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Abstract - *This study suggests a hybrid renewable energy-based infrastructure for charging EVs during grid outages with varying scaled electric vehicle sessions. The objective is to design the most reliable electric vehicle charging station from the energy delivery point of view for the incoming electric vehicles to charge. For this, we modelled a case study considering different renewable energy systems, grid outages, and a varying population of incoming electric vehicles. First, a resource assessment was done to understand the renewable resource potential in the study region. Second, based on the resource assessment results, a charging infrastructure was planned and modelled. While modelling, the realistic loads of electric vehicles, and realistic power outage events and duration for restoration are considered. Third, to optimally balance the power exchanges and to manage energy, we proposed a peak shaving controller. Fourth, a detailed techno-economic and environmental modelling was done using a hybrid optimization tool called Homer Grid, followed by sensitivity analysis. Results show that 100% renewable-based charging infrastructure is possible under varying grid outage and scaled electric vehicle sessions, but at the cost of increasing capital investment. The sensitivity results suggested that there could be a high possibility for lowering the charging infrastructure cost as well as operating and maintenance cost if the renewable fraction is close to 80%. Lastly, this paper proposed the most feasible optimized charging infrastructure structure for charging electric vehicles from a techno-economic and environmental viewpoint, which could foster the electric vehicle deployment.*

Keywords - *Charging infrastructure, Electric vehicles, Grid outages, Hybrid renewable system, Peak shaving controller.*

1. Introduction

The decarbonization of the transportation industry results from the escalating concerns about environmental change due to different causes and the related problems associated with energy derived from fossil fuels. The transportation industry continues to be responsible for 24% of direct CO2 emissions, according to the International Energy Agency (IEA, 2020), which are mostly due to the consumption of fossil fuels. This suggests converting to renewable energy for transportation. This pressing demand drove electronic mobility, resulting in the development and commercialization of Electric Vehicles (EVs). EV usage is gradually increasing, but still trails behind the highly developed and persistent charging stations required for charging automobiles. As an outcome, charging stations were set up and primarily supported by the electrical grid, which drew criticism for both their technological merits and environmental benefits [1]. Many issues with the technical components need to be addressed, such as power losses, voltage stability, a rise in maximum load and reliability. The aforementioned are the primary influences on the power sector. The grid energy combination was the focus of most sustainability-related worries; for instance, a nation where a sizable portion of EVs are powered by fossil fuels may not be viable [10]. Additionally, it is possible that their involvement in power balancing and energy management services is not sustainable. Furthermore, their involvement in power balancing and energy management services may not be long-term [19]. Ensuring green energy was given prominence in light of the challenges stated, resulting in the development of renewable resource-based charging stations for electric vehicles [20]. Experts thus started concentrating their efforts on creating electric vehicle charging stations that use sustainable energy sources. In order to better comprehend the developments in the charging infrastructure study, we did a thorough literature review.

After conducting a study on renewable energy sources, [18] came to the conclusion that renewable energy might be employed as the power source in off-grid mode for EV charging. [16] employed a solar Photovoltaic (PV) array, a single voltage source converter, a storage battery in conjunction with a diesel generator and the grid to power the EV charging infrastructure. Later, when optimization-influenced judgments became more prevalent, researchers began using heuristic optimization methods to further enhance performance and infrastructure sizing. To demonstrate the feasibility of the EV charging system, [6] examined a queuing strategy for a chaotic optimization problem involving EV charging stations and RESs. To calculate the integrated EV charging station size for renewable energy sources, particle swarm optimization and the genetic algorithm were demonstrated [15]. An integrated power system approach is also used in the construction of commercial EV charging infrastructure [3]. The implications of integrating a huge number of EVs into the electrical system were investigated by [17].

In order to charging three-wheelers on the road in developing countries, Later, the PV plus biogas-based EV charging station was designed by Podder et al. [13] They said that integrated systems based on renewable energy are more dependable for supplying EVs with power [12, 14] found that the load increases by 2% for 15 EVs and 7% for 50 EVs when they are integrated. So, from the literature review, it is understood that planning EV charging infrastructure needs strategic involvement of energy systems, storage systems, and the EV population coming in for charging. On the other hand, researchers have also stated that reliable operation is the most crucial point that needs to be considered while modelling. However, reliability issues are ignored and less considered while modelling. So, to fill this gap, this study accounts for varying grid outages and scaled EV sessions for planning EV charging infrastructure. Additionally, this study examined the proposed EV charging system's comprehensive techno-economic and ecological sustainability assessment.

2. Framework

The framework is presented in Figure 1(a), where a time versus load plot depicts that any power source can adjust to compensate for a disrupted load and sets the standard for how effectively the charging infrastructure should perform. It implements a power governance function to comprehend the dependable performance of the planned charging system; see Equation (1), which is subjected to grid outages, and the number of EV sessions per day.

$$P_{EVCS} = f(P_g, P_{EVi}, P_{REj}, P_{DG}) \quad (1)$$

Where P_{EVCS} is the power needed by the EV charging station; P_{EVi} is the power required by an electric vehicle, where ii is the variation in sessions, i.e., visits/day; P_g is the grid power P_{REi} is the power from renewable energy sources where j represents solar, wind, and other renewable sources; P_{DG} is the power from diesel generator. According to Equation (1), the power is maintained in accordance with the consistent working circumstance. For instance, if there were problems with the grid, renewables would support; if the problems were with renewables, the grid would offer assistance. If both the grid and renewables were unable to meet the demand, then DG should support.

3. Electric Vehicle Charging Infrastructure Modelling

In light of the framework proposed in Section 2, the charging station depicted in Figure 1 is taken into consideration.

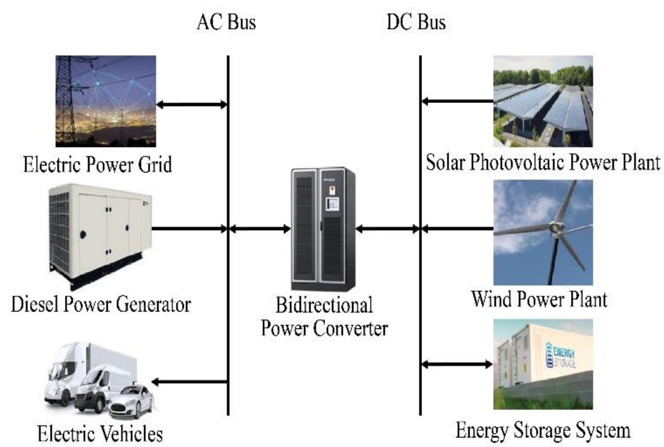


Fig. 1 Schematic representation of proposed EV charging infrastructure

This charging station has a solar power plant, a wind power plant, a diesel generator-based power plant onsite that powers the grid, and an EV charging station to ensure dependable operation. In addition, a bidirectional power converter unit is employed to ensure Direct Current (DC) to Alternating Current (AC) and vice versa. This power converter is positioned between the DC and AC bus. Grid, diesel generator, and EVs are connected to the AC bus, whereas solar and wind systems are connected to the DC bus. he intricate modeling of the many parts of the EV charging station shown in Figure 1 is discussed in the sections below.

3.1. Electric Power Grid and Electric Vehicle Load

The transportation of power from generators to consumers is accomplished via a network of connected electrical grids. The size of the electric power grid varied in most cases. However, one can tap the power from the grid by integrating their system by matching frequency. Here, in our model, we ensured the same. While modelling, the duration of power outages, the number of outage events, and the restoration time are considered. Coming to the EV load, a population of 100 EVs is taken into account. The highest power needed to charge a vehicle is 150 kW, and the typical charging time for a vehicle is 50 minutes. While modelling the electric vehicle load, varying sessions are considered.

3.2. Modelling of a Solar Photovoltaic Plant

The grid and the onsite solar power plant are the two power sources for the suggested system, as seen in Figure 1. According to previous study, Equation (2) provides the electric power output of the PV plant.

$$P_{pv} = \eta_{pv}.A_{pv}.\eta_{pc}.G_{pv}(1 + \gamma(T_c - T_{ref} \quad (2)$$

Where η_{pv} indicates solar PV power conversion efficiency, Power converter efficiency is denoted by ηpc, and Ppv is the photovoltaic power; The solar PV array's surface area is denoted by Apv. γ is the temperature coefficient; Gpv denotes solar radiation impacting on the solar PV array; The reference temperature is denoted by Tref, while Tc is the temperature of the solar PV cell. The power performance of solar PV plants is greatly influenced by temperature. Therefore, researchers examined the power that was affected by temperature. Therefore, Equation (3) provides a model for calculating the cell temperature [8, 11].

$$T_c = T_a + mc\left(\frac{0.32}{8.91+2W_s}\right).G_{pv} \quad (3)$$

Where mc is the mounting coefficient for rooftop or integrated system, W_s indicates the speed of the wind, and T_a represents ambient temperature.

3.3. Modelling of the Wind Power Plant

As shown in Figure 1, a wind turbine constituted one of the energy-producing elements in the proposed EV charging infrastructure.

A wind turbine generates power using the kinetic energy present in the wind. We modelled the power model using the well-known Betz' Law, see Equation (4).

$$P_{WT} = \frac{1}{2}C_p\rho AW_s{}^3 \quad (4)$$

Where ρ represents air density, C_p is the coefficient of power for the wind turbine. A is the area of the wind turbine blade, and the wind speed is represented by W_s.

3.4. Modelling of the Diesel Generator

The EV charging infrastructure must include DG since it provides numerous advantages in terms of emergency backup power and system dependability. Its modelling is as done as per Equation (5).

$$Diesel\ consumption = \sum_{i=1}^{n}\left(a + bP_i + cP_i^2\right)\{\$/hr\} \quad (5)$$

3.5. Modelling of an Energy Storage System

The Energy Storage System (ESS) is modelled as a charging station. According to the EV fleet, the discharging and charging patterns of the charging station are determined by Equations (6) and (7). There are 40 chargers in this instance, and each one has a 150 kW capacity.

$$\sum_{t=1}^{n} ESS = \sum_{t=1}^{n}[\left(ESS(t-1).\left(1 - DR_{self}\right)\right)\left((P_g + P_{pv}) - P_{ev}\right).\eta_{pc}.\eta_{ess}] \quad (6)$$

$$\sum_{t=1}^{n} ESS = \sum_{t=1}^{n}[\left(ESS(t-1).\left(1 - DR_{self}\right)\right) + (P_{ev}.\eta_{pc} - (P_g + P_{pv}))] \quad (7)$$

Where t indicates time starting from 1 to nn.

DR_{self} represents the self-discharge rate of the storage system, P_{ev} represents EV's power profile, and η_{ess} is the energy storage system's efficiency,

3.6. Modelling the Bidirectional Power Converter

A power conversion unit is an apparatus that transforms the direct current generated by a solar PV array into alternating current and vice versa in order to use grid electricity to charge an energy storage system.

The operation of power converters is determined by Equation (8).

$$P_{pc} = \eta_{pc}.(P_{pv} + P_{WT} + P_{ESS} \quad (8)$$

Where P_{pc} represents output power from the power converter

4. Simulation Methods

4.1. Optimization using Homer Grid

A system simulation model was created using the HOMER Grid tool based on the mathematical model mentioned in section 3 (HOMER Grid, 2021).

The controller was an essential one while modelling; for this, a peak-shaving technique was used. MATLAB 2019 (MathWorks, 2019) was used to model these peak shaving strategies, which were subsequently connected to the HOMER Grid tool for analysis and simulation. Using HOMER Grid, the system's techno-economic potential was well observed; however, environmental aspects were only obtained for the diesel generator. For this, techno-economic modelling is done in HOMER Grid. The HOMER Grid optimization method optimizes the charging station by maximizing the Renewable Fraction (RF) and Cost Of Energy (COE) and lowering the Net Present Cost (NPC). The share of energy derived from RERs used to meet the load is typically represented as the renewable fraction. Using Equation (9), the renewable fraction is calculated in the proposed charging station [8].

$$RF = 1 - \frac{E_{DG}+H_{Thermal}}{E_{Reserve}+H_{Therma\ Load}} \quad (9)$$

The Cost Of Energy (COE) and Net Present Cost (NPC) are determined using Equation (10) and (11) [8].

$$NPC = \frac{TAC}{CRF(i,Rpr_j)} \quad (10)$$

$$\text{COE} = \frac{TAC}{L_{prim,AC}+L_{prim,DC}} \quad (11)$$

The suggested controller proactively regulates the total load demand of electric vehicles while also removing the short-term demand spikes. For implementing this approach, we employed an optimization strategy that chose the shaving level determined by Equation (12) while minimizing the optimized function presented in Equation (13) (Tengnér, Karmiris, 2013)

Objective function:

$$\min f(x) = \left| C_{ess} - (max \int_{t0}^{t} L(t).dt - min \int_{t0}^{t} (L(t) - x).dt) \right| \quad (12)$$

Levelling constraints:

$$L(t)_{max} < x < L(t)_{min} \quad (13)$$

The simulated model in HOMER Grid is shown in Figure 2.

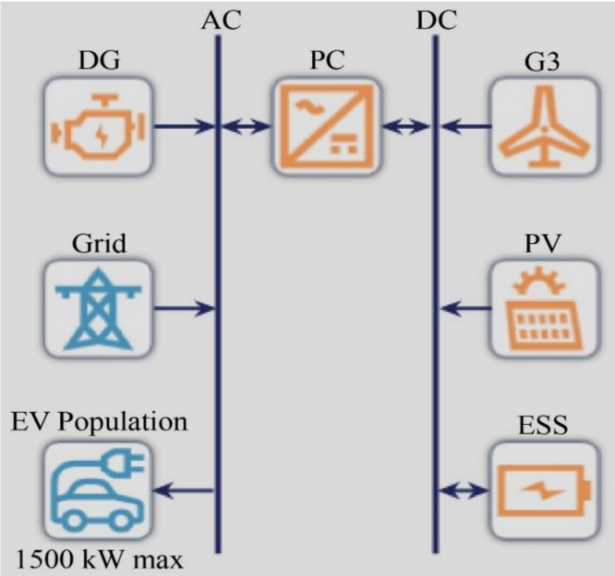


Fig. 2 Charging infrastructure simulated in HOMER Grid

4.2. Carbon Footprint Model

The results of the HOMER Grid tool were exported to the Excel sheet, followed by a custom-built Excel model to simulate the carbon footprint for each of the components used in EV charging infrastructure. This model considers the environmental footprint results of the diesel generator from the Homer optimized model. For the rest, we followed Equation (14) (Kumar et al., 2020).

$$\text{CF} = E_{ni} \times EF_i \quad (14)$$

Where E_{ni} is the energy in kWh for device i; EF_i is the emission factor of the device i.

5. Results and Discussion

The simulated outcomes of the suggested EV charging infrastructure are shown in this section. The findings include the impact of daily EV sessions on infrastructure design, scaled EV session effects on microgrid power balances and performances.

5.1. Analysis of the Charging Station Design

The average number of EV visits to the charging station over a 24-hour period is shown in Figure 3. According to this, the applied fragile scenarios of sessions per day, ranging from 15 to 45, had a significant effect on the energy delivered by the charging station. Table 1 summarizes the profile of the session and its implications for energy served and peak demand.

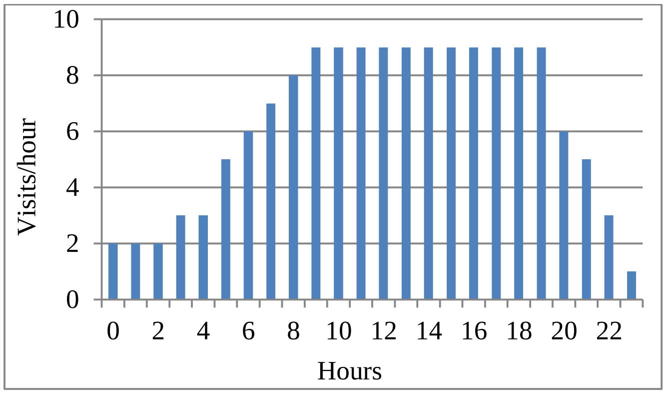


Fig. 3 Profile of an electric vehicle at the charging station

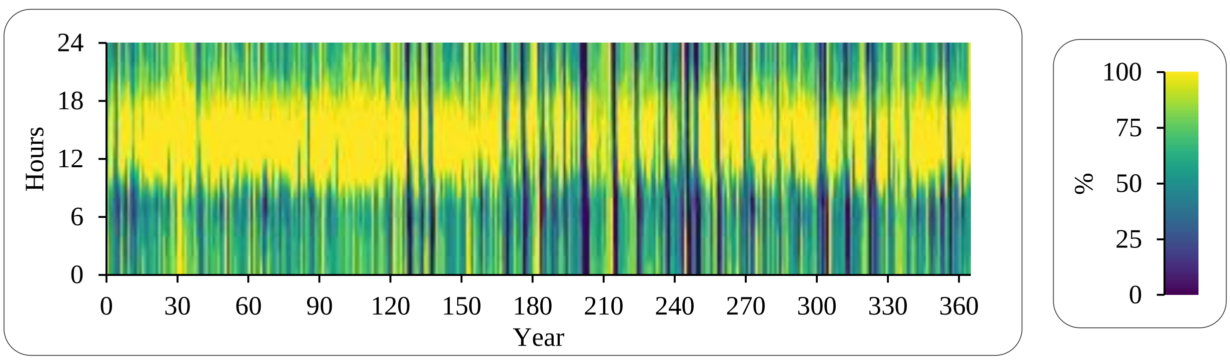
The measured peak power consumption ranged from 475 to 900 kW, as shown in Table 1, and the number of energy storage strings needed differed from 8 to 21. The energy storage system features and outcomes of the charging station are shown in Table 2. The range of the nominal Capacity is 1680–4410 kWh. While the energy losses range from 33,120 to 89460 kWh/year, the measured yearly Throughput differs from 552000 to 1491000 kWh/year.The results of the status of charge are shown in Figure 3. To meet these fluctuating energy demands, the microgrid system's design size also changed. This impacts the microgrid's component sizing, which is thought to be used as a power source for a charging infrastructure. Grid assistance was also taken into account to guarantee dependable functioning.

Table 1. Summary of electric vehicle charging session

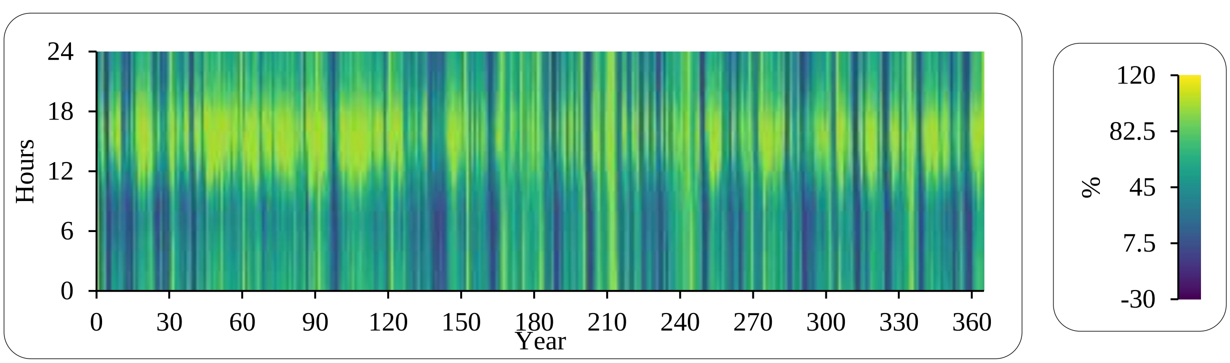
Sessions/Day	Sessions / Year	Energy /Session (kWh)	Energy Storage (MWh)	Annual Energy Served (kWh)	Peak Power (kW)
15	5,414	130	8	704,820	475
25	9,131	130	13	1,186,030	675
35	12,784	130	18	1,662,020	770
45	16,436	130	21	2,136,680	900

Table 2. Sizing and energy results of the Energy storage system

Quantity	Values for each Instance of Scaled Sessions Per Day			
	15	25	35	45
Properties of Energy Storage				
String Size (batteries)	1.00	1.00	1.00	1.00
Batteries (quantity)	8	13	18	21
Strings in Parallel (strings)	8.00	13.0	18.0	21.0
Statistics of Energy Storage				
Lifetime Throughput (kWh)	5,520,000	8,617,500	11,932,500	14,910,000
Nominal Capacity (kWh)	1680	2730	3780	4410
Projected Life (yr)	10	10	10	10
Results of Energy Storage Data				
Losses (kWh/yr)	33,120	51,705	71,595	89,460
Annual Throughput (kWh/yr)	552,000	861,750	1,193,250	1,491,000
Storage Depletion (kWh/yr)	-1,680	-2,730	-3,780	-4,410



(a)



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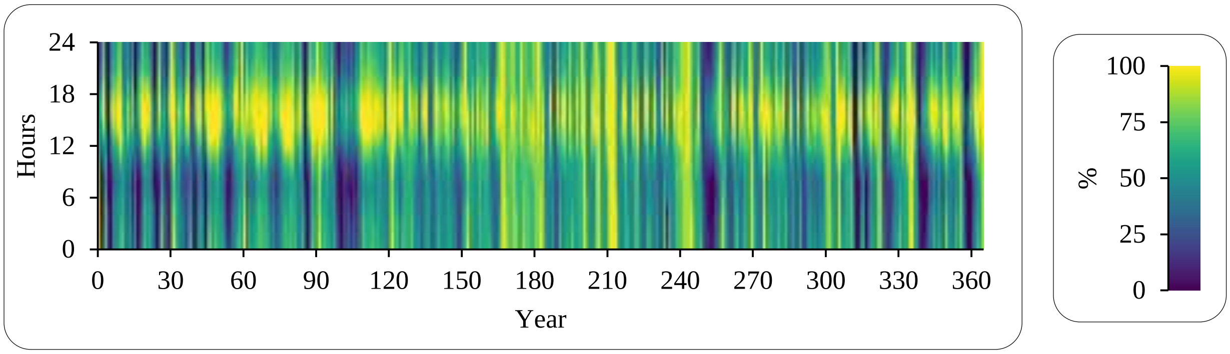

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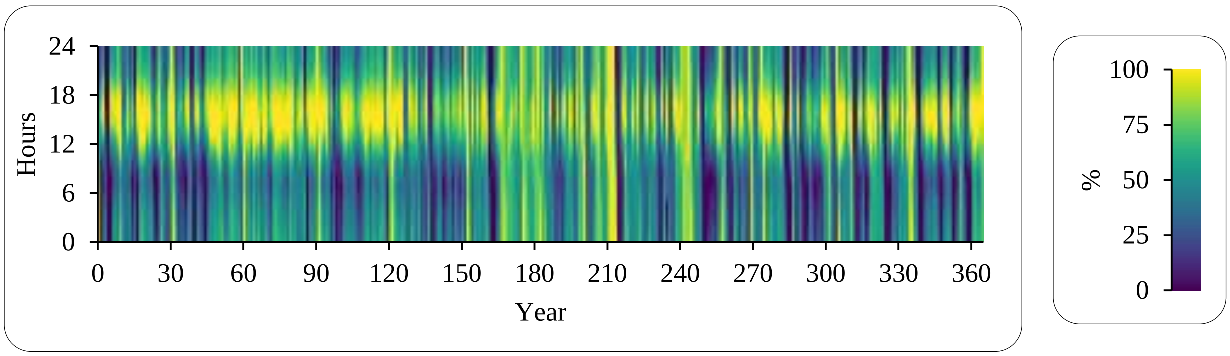
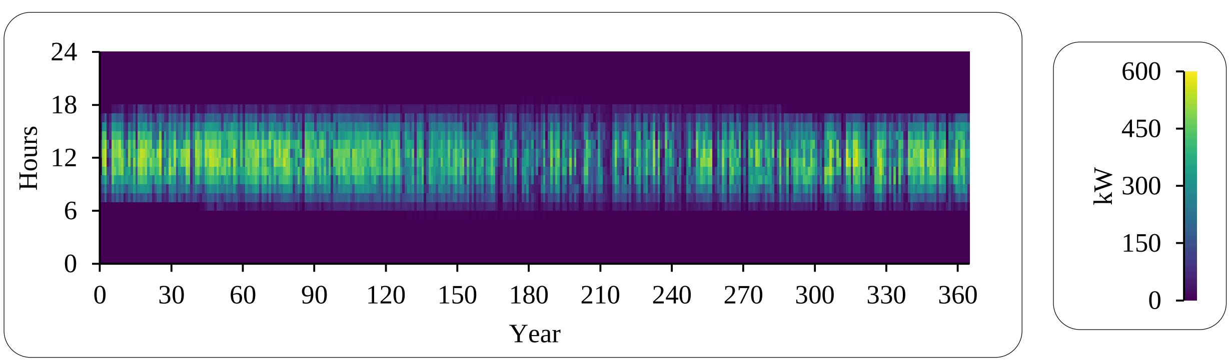


(d)

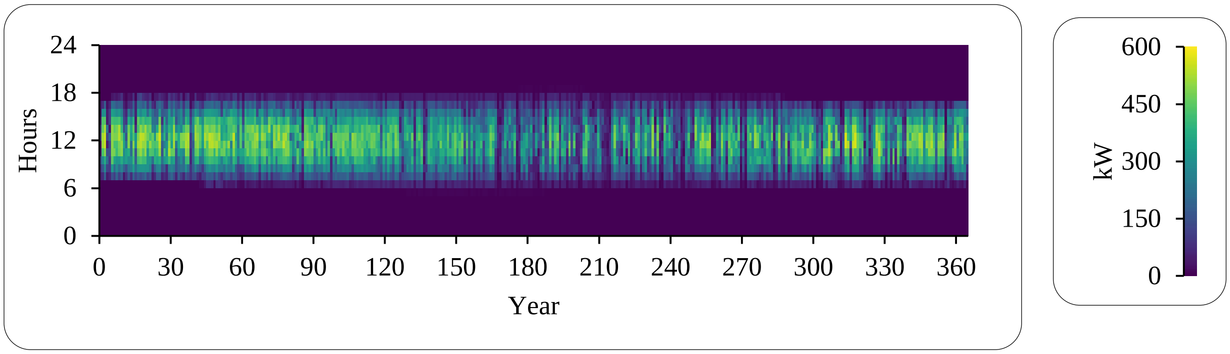
Fig. 4 Compared to the scaled average daily sessions, the energy storage state of charge in percentage: (a)15, (b)25, (c)35, and (d)45.

5.2. Power Performance of Generation

Three power sources-solar, wind, and diesel-are used in the proposed charging infrastructure. The DMap displaying the solar PV power outputs for the entire year is seen in Figure 5. As a backup, the grid supplies and consumes energy based on the state of surplus and deficit resulting from the unpredictable functioning of renewables. Furthermore, the controller will guarantee the operation of renewable energy systems or, in the worst situation, a diesel generator, depending on the grid outage criteria specified below. The charging station's power imports from the grid are depicted in Figure 6.



(a)



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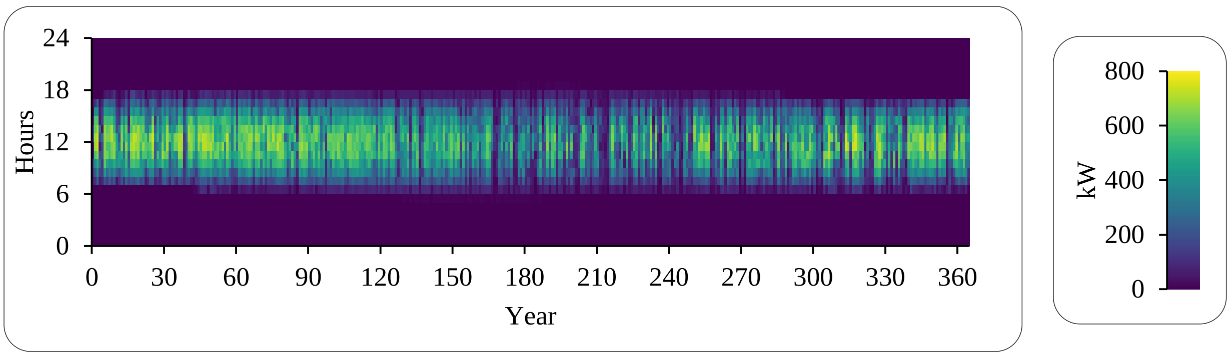

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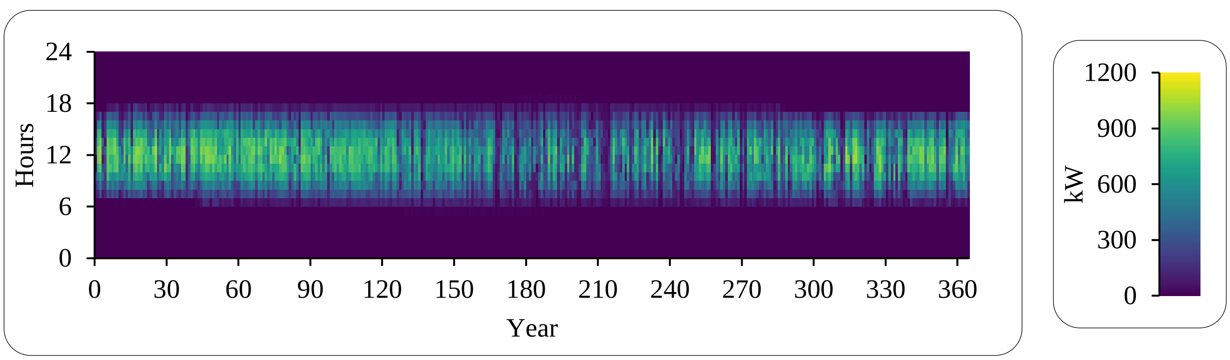
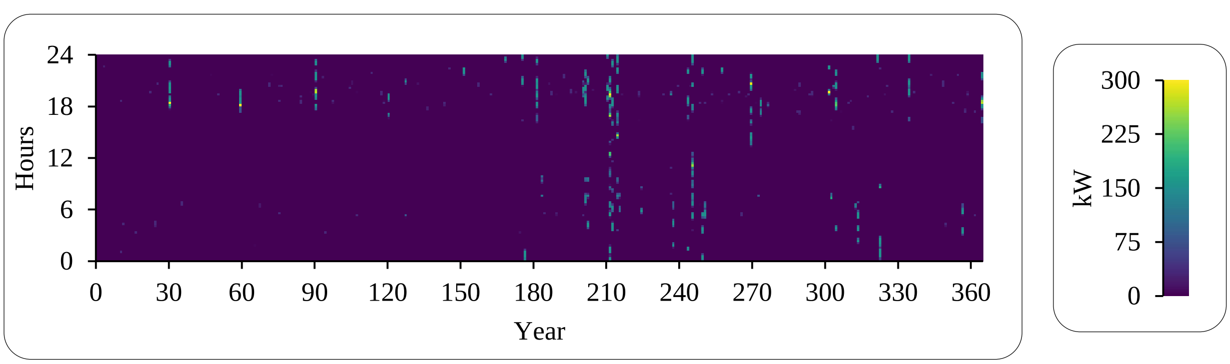
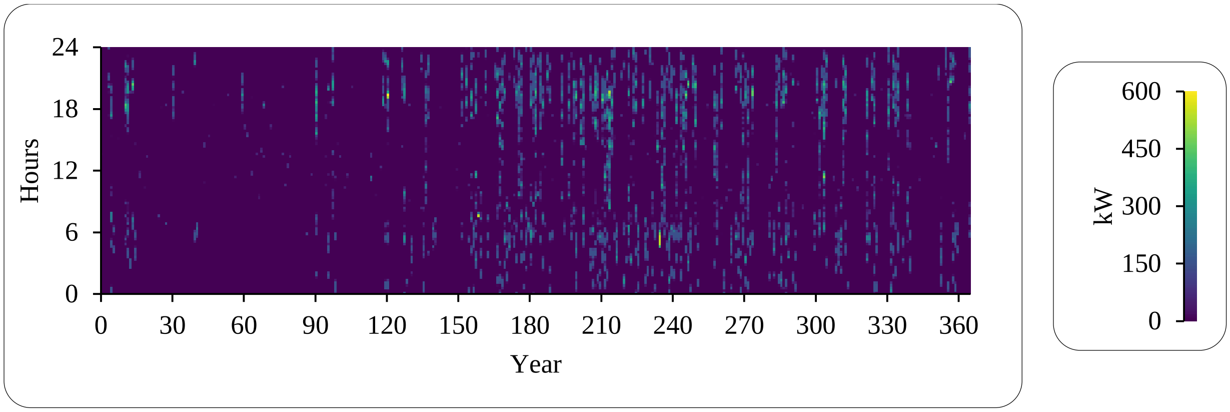


(d)

Fig. 5 Power output determined by scaled average daily sessions from the hybrid renewable power plant (diesel, wind, and solar) (a) 15, (b) 25, (c) 35, and (d) 45.



(a)



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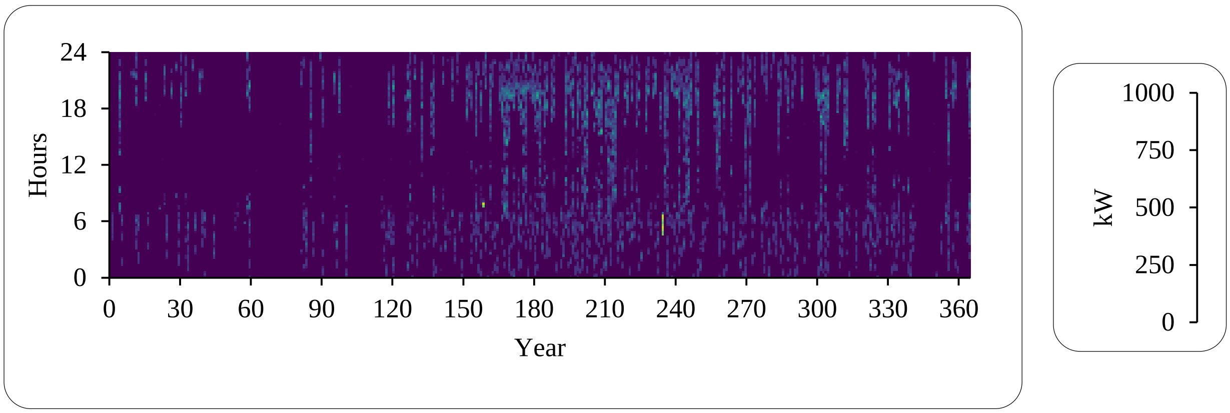

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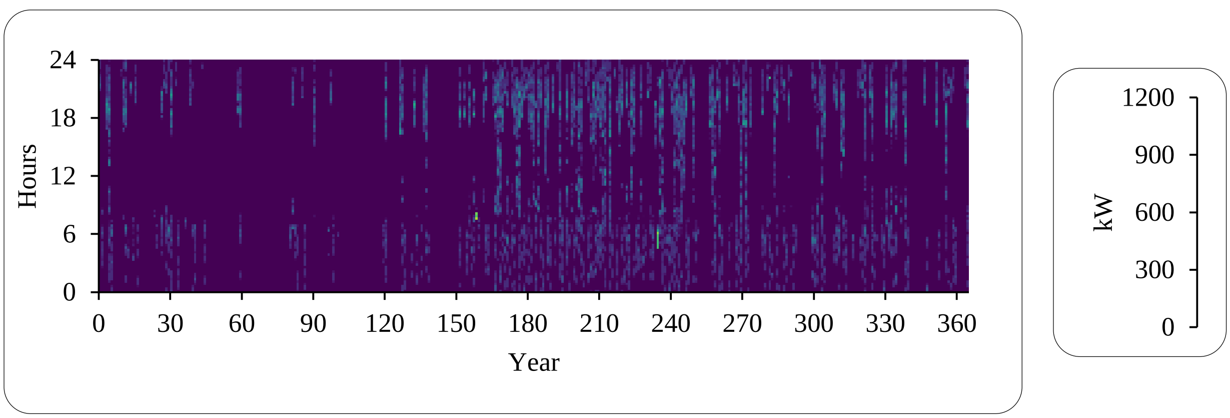


(d)

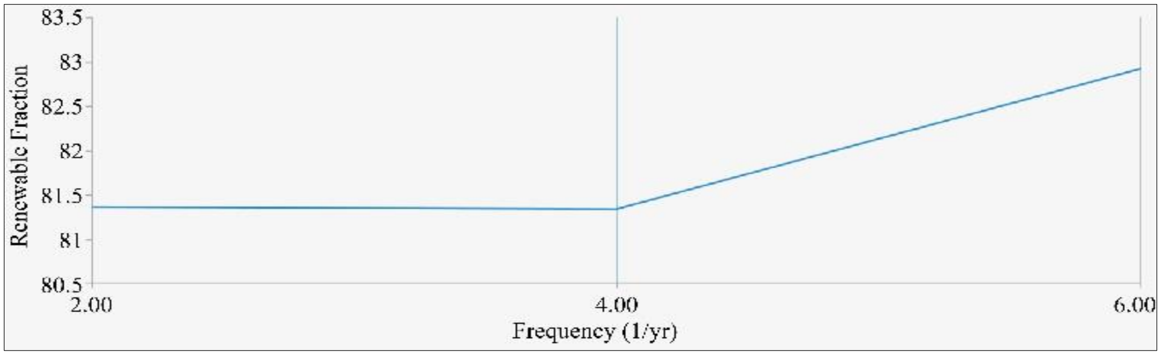
Fig. 6 The scaled average daily sessions for power imports from the network (a) 15, (b) 25, (c) 35, and (d) 45.

5.3. Impact of Grid Outages and EV Session on Renewable Fraction

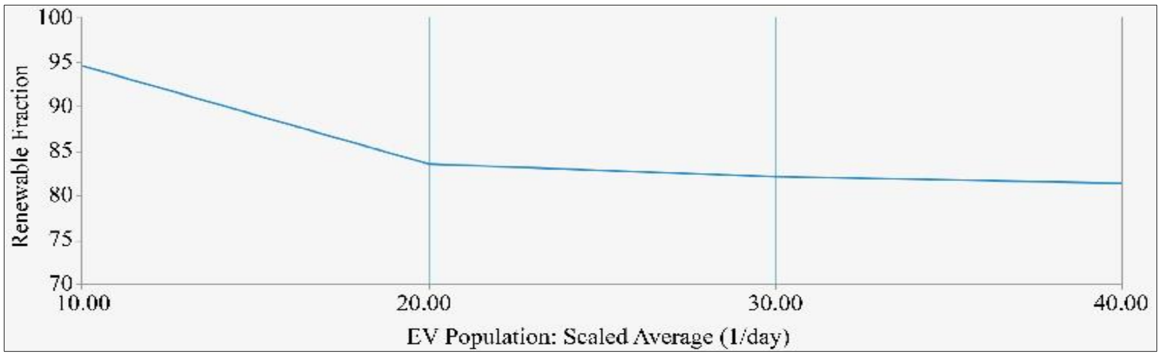
Figure 7 shows the impact of grid outages and scaled EV sessions on the renewable fraction. Figure 7(a) shows that as the grid outage frequency increases, the renewable fraction increases, which is in line with the framework governance that we proposed in Section 2. Suppose we see the impact based on the number of EV sessions in Figure 7(b). In that case, the renewable fraction tends to decrease, and this is due to the amount of energy required; in that case, renewables may not support, and the system has to depend upon the grid or a diesel generator. As a result, there has been a decrease in the renewable fraction with the increase in sessions.

5.4. Impact of Grid Outages and Scaled EV Sessions on Economics

Figure 8 shows the impact of grid outages and scaled EV sessions on the total net present cost and cost of energy. Figure 7 shows that as the grid outage frequency increases, the total net present cost increases.



(a)



(b)

Fig. 7 Variation in renewable fraction (a) Due to grid outages, and (b) Due to the EV session.

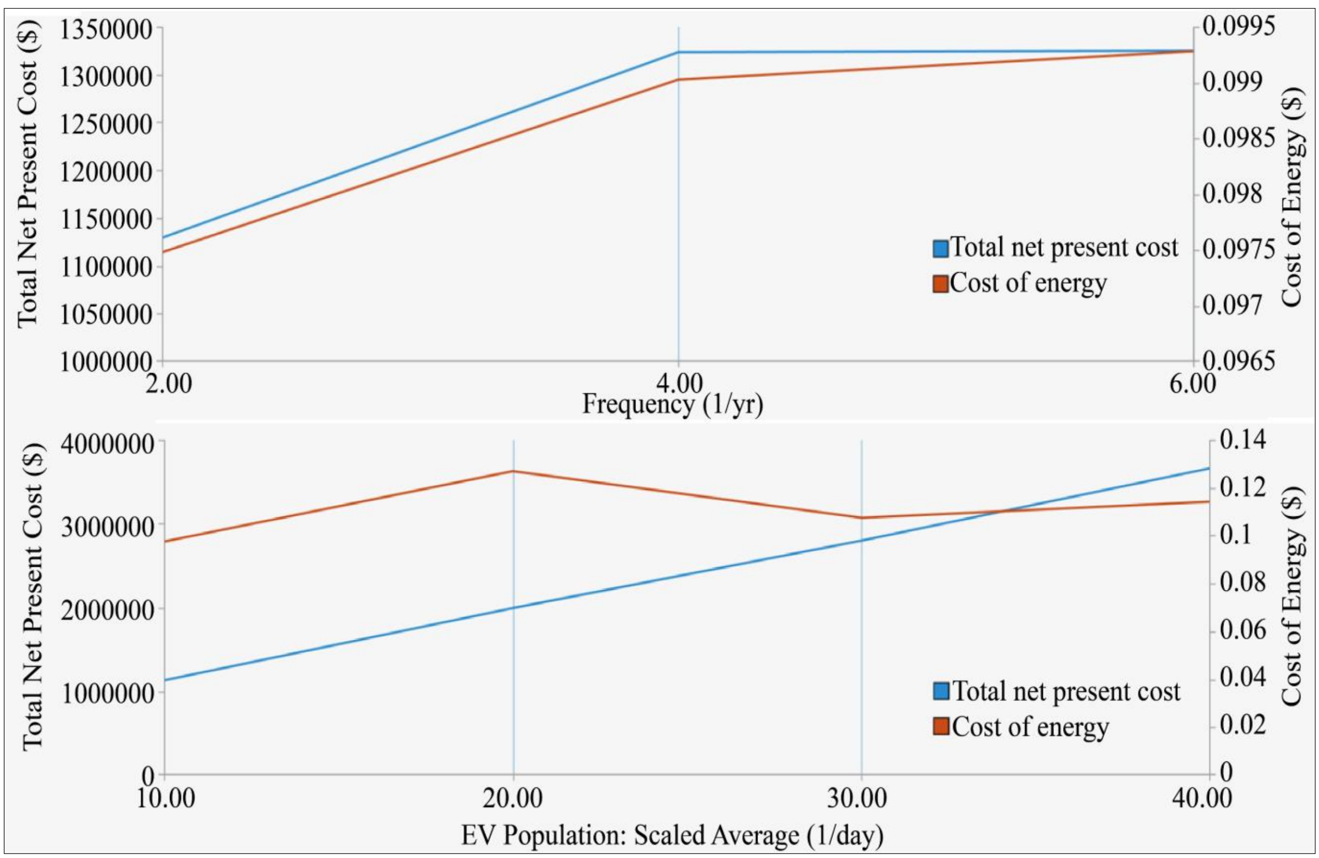


Fig. 8 Variation in total net present cost and cost of energy due to Grid Outages and EV sessions

This is because when the grid fails, the charging station has to fully depend upon the onsite renewables. That is the reason the design was considered to take reliability and failure situations into account during optimization. The same can be seen with the cost of energy. If we see the impact based on the number of EV sessions in Figure 8, the total net present cost tends to increase, and this is due to the amount of energy required. On the other hand, the cost of energy fluctuated because of the energy availability from renewables and the grid.

Table 3. Environmental footprint results of EV charging infrastructure

Emission Parameter	PV + WT + DG + ESS +Grid
CO_2	94,322.69
CO	246.17
UHC	6.81
PM	0.96
SO2	87.34
NO2	883.36

5.5. Carbon Footprint Results

The environmental footprint, particularly greenhouse gas emissions and other parameters, is observed and presented in Table 3. From Table 3, when compared to all emission parameters, the CO_2 emissions are very high, followed by NO_2, CO, and others.

6. Conclusion

This article suggests a blend of renewable energy sources for an EV charging network. After designing and modeling it, an analysis is conducted. In four different situations, depending on the scaled averaging session each day, realistic EV loads are considered and simulated during modeling. 80% of the energy in the suggested model came from renewable sources, while only a small portion came from exports and imports to the network. This demonstrated unequivocally that EV charging infrastructure might be considered grid-independent; Therefore, grid connectivity and dependency are recommended in light of uncertain renewable operation and grid interruptions. The economic findings also demonstrated that grid disruptions and scaled EV sessions will have a major impact, which should be taken into consideration when designing EV charging infrastructure.

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