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Research Paper

Analysis of microgrid integrated Photovoltaic (PV) Powered Electric Vehicle Charging Stations (EVCS) under different solar irradiation conditions in India: A way towards sustainable development and growth

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ABSTRACT

The depleting fossil fuel and growing environmental concern have opened the doors for clean and green energy development using renewable energy sources. Also, the growing oil demand and carbon emissions have created a huge scope for Electric Vehicle (EV) usage across the world which has resulted in blooming EV market. Photovoltaic (PV) powered EV charging can substantially reduce the carbon foot prints when compared to the conventional utility grid based EV charging. The amalgamation of solar power and EV charging is one of the best methods in sustainable development for EV market. Recent statistics suggest that usage of EVs in different cities in India has proliferated and the development of the charging infrastructure is a big challenge for the densely populated country. *Firstly, theoretical demand model and* stochastic model for EV traffic and resource utilization pattern *is developed*. Secondly, the optimal configuration and techno-economic assessment of Solar powered EV Charging Station (EVCS) in microgrid is analyzed for four different Indian cities (Shillong, Bengaluru, Jaipur and Kashmir) with varied solar radiation conditions. *Lastly, the environment benefits of solar PV powered EVCS are assessed and analyzed.* The results demonstrate that the optimal configuration and investment efficiency in each urban area is greatly affected by the solar irradiation and feed-in-tariff (FIT) price of rooftop solar power. Kashmir with high solar irradiation conditions can invest in the solar EVCS compared to the other cities.

1. Introduction

The depleting fossil fuels, serious environmental concerns and abrupt climatic changes have opened the doors for the development of clean and green energy for sustainable development and growth (Minh et al., 2021; Aziz et al., 2018). Agreements have been signed by many countries at different platforms across the world to reduce global climate change (Hampannavar et al., 2021a). Government of India (GoI) is promoting the generation of renewable energy and is on 5th position in the World in terms of renewable energy installed capacity (Singh and Arya, 2019). The green energy corridor project gives a required push to support renewable energy generation and interstate transmission lines of 9600 ckm lines are constructed by the states having high solar and wind potential. The wind energy installed capacity in India is 38.78 GW (4th largest installed capacity in the world) as on 28th February 2021 and solar energy installed capacity is 45 GW (5th largest installed capacity in the world). Ministry of Power (MoP) is also planning for the installation of off shore wind energy in the states of Tamil Nadu and Gujarat (Wang and Wang, 2013). With this initiatives India is planning for huge renewable energy expansion and very ambitious to top the list in the renewable energy installed capacity. With the developments in the EV technology and the grid advancements, group of EVs known as Vehicle-to-Grid (V2G) can participate in the power transaction with the grid and contribute to grid requirements. Majority of the vehicles are parked 90%–95% of the times and they can be used for power exchange with the grid. V2G supports peak shaving, valley filling, load leveling, load shifting and the internal capacitor of the EV battery supports reactive power support to the grid (Yilmaz and Krein, 2013). V2G can also be considered as substitute for spinning reserve. EVs play a prominent role in power grid and contribute tremendously to support time varying

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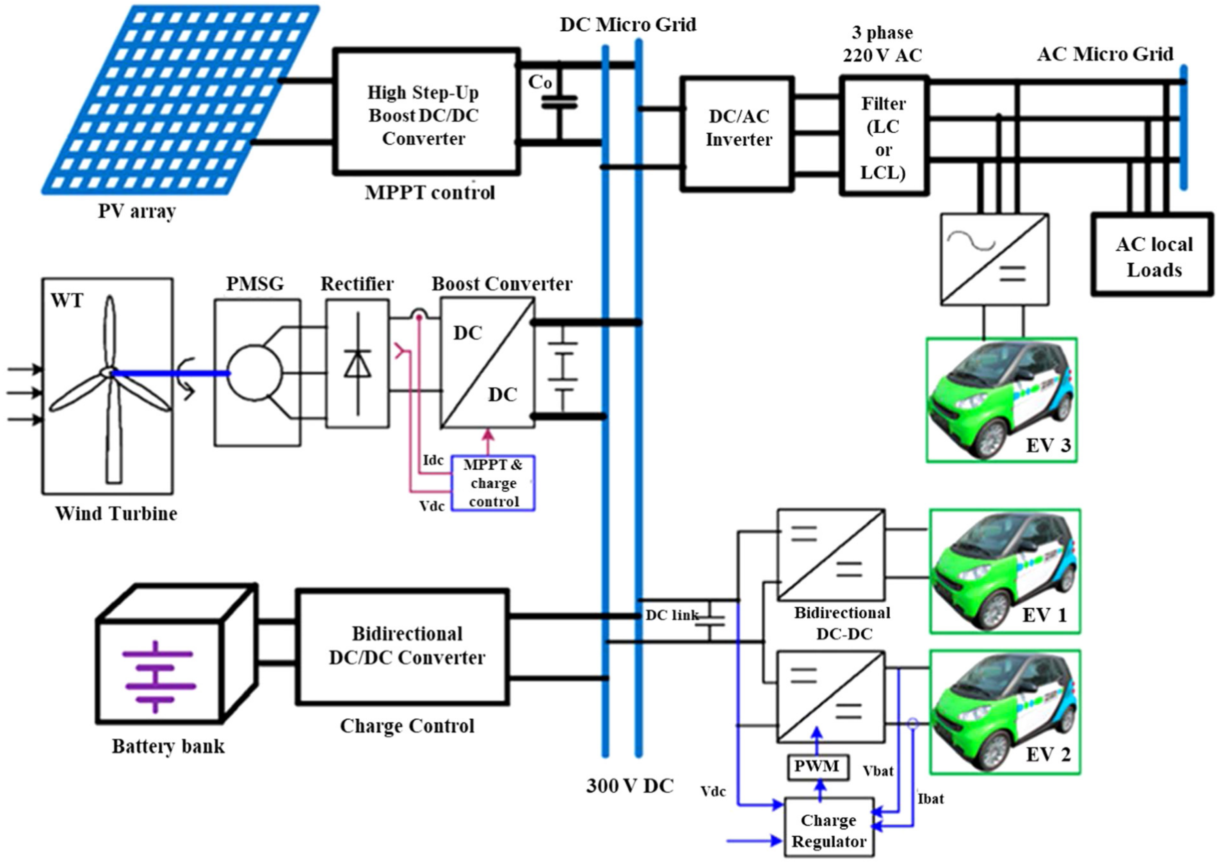


Fig. 1. Conceptual view of microgrid.

load demand and the development of crucial charging infrastructure with different topologies are important (Yilmaz and Kurien, 2013). The impact of EVs on utilities and distribution network are matter of great concern and are reviewed in Hexeberg (2014).

There are different types of EVs: hybrid EV, fuel cell EV plug-in hybrid EV (PHEV) and battery EVs. There are three ways to charge EVs: Vehicle-to-Vehicle (V2V), Vehicle-to-Home (V2H) and V2G. The concept of smart charging is presented in and three ways to charge EVs: Vehicle-to-Vehicle (V2V), Vehicle-to-Home (V2H) and V2G are presented in Contreras-Ocana et al. (2016). The efficient optimal scheduling of charging station for EV interaction is dealt in You and Yang (2014) and consumer choices, preferences of EVCS are discussed in Hardman et al. (2018). The standards for EV charging are: International Electrotechnical Commission (IEC), CHArge de MOve (CHAdeMO) and Society of Automotive Engineers (SAE). IEC and SAE has both AC/DC charging and CHAdeMO has only DC charging. AC charging types: Level-1 (4–7.5 kW/16 A), Level-2 (8–15 kW/32 A) and Level-3 (60–120 kW/250 A) and DC charging type: CHAdeMO (240 kW/400 A) and the power converter design details are explained in Kutkut and Klontz (1997). The state of art EV technologies and its impact are expressed in Williamson et al. (2015) and future electric transportation requirements in terms of technical/management are presented in Kumar et al. (2017). The charging infrastructure must comply with IEEE 1547 2003 standard and two types of V2G integrators are available: On-board and Off-board. The design and implementation of V2G integrator for On-board is presented in Neumann et al. (2012). EV battery plays a vital role in storage system as one EV may not make the difference but group of EV batteries can definitely make a huge difference. Charging process influences battery life, charging energy efficiency and charging time (Ashish Kumar Karmaker et al., 2020). EV charging by fossil energy sources cause environmental pollution and recent literature studies suggest that PV, wind and biogas are used for EV charging to combat this issue. Parking lot using rooftop PV power for charging are simulated in Letendre (2009) and EVCS using biogas as source was discussed in Kumar and Udaykumar (2015). The economic efficiency of PV powered EV charging is presented in Kumar and Udaykumar (2016). Stochastic modeling of EV arrival to the grid was discussed in and impact of EV charging on the grid was presented in Sayed et al. (2019). This decade has seen tremendous push in EV manufacturing throughout the world and Govt. of India is also contributing to promote EVs on road by providing subsidies and supporting schemes. The development of charging infrastructure for EVs is a challenging task and many countries have made it functional. The role of EVs in power grid plays a vital role in demand response management.

India is gifted with sufficient Solar and wind sources which can be used for power generation thereby relying on the thermal power plant can be reduced. National Institute of Wind Energy (NIWE) proposed that 302 GW of power can be generated from the wind and MoP is working on the same. On the similar lines National Institute of Solar Energy (NISE) in association with MoP and Ministry of New and Renewable Energy (MNRE) is ready to setup 100 GW of solar PV by 2022. The ever growing population in India, peak energy demand, electrification in terrain regions and relying on Thermal Plants are some of the factors which serve as a motivation for this work. There is no existing literature available which describes solar PV powered EVCS for different regions in Indian context. Four locations Shillong, Bengaluru, Jaipur and Kashmir were chosen with different solar irradiation conditions in this paper. Shillong is in North Eastern India which represent the terrain regions; Jaipur has huge solar potential which is located in North Western India, Kashmir is a valley and

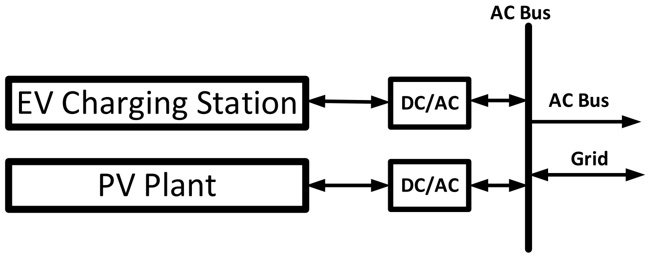


Fig. 2. MG layout.

situated in North India and Bengaluru is information technology hub located in South India. Solar PV powered electric vehicle charging system (EVCS) in Microgrid is proposed for all these locations.

The significant contributions of this paper are:

(i) Theoretical demand model and stochastic modeling of EV arrivals, resource utilization and analysis of parking lot occupancy in microgrid.
(ii) Optimal configuration and techno-economic assessment of PV power based EVCS in community a microgrid.
(iii) Environmental assessment of PV power based EVCS and benefits are presented.

The results and the inferences drawn from the study not only draw the attention of policy makers but also promote the EV industry in India and surrounding countries.

2. System description

Microgrid (MG) improves energy chain efficiency and effectively complement the power grid (in terms of reliability and quality of power). MG with hybrid generations with EVs and load are shown in Fig. 1 (AbuElrub et al., 2020) and it depicts that PV array, wind turbine (WT) are connected to the DC bus through essential power electronics interface. EVs are connected to both AC/DC buses for possible power transaction with the grid. The energy efficiency, reliability and flexibility is improved with reduced energy consumption. Renewable sources are used to generate power in community microgrid and due to the intermittent nature of the sources, energy storage is required. The surplus power generated is stored in battery and later sold to the grid. This can be achieved by V2G operation. The MG layout is shown in Fig. 2 which consists of AC load, utility grid and PV system connected to the AC bus through converter and bidirectional EVCS. Merits of the suggested system are: (i) energy imported from the grid is decreased since PV generates power locally, (ii) EV batteries act as energy storage devices to store excess power which minimizes negative impact of the PV on the distribution network and (iii) Long idle times of EV can be used for V2G operation (Hampannavar et al., 2021b).

2.1. Solar PV

Solar energy is available in abundant for several hours of the day throughout the year in some locations. This energy is harnessed using PV panels to produce DC power and inverters are used to convert DC–AC to connect it to the grid. Solar power is intermittent in nature and depends on ambient temperature and solar radiation. Intermittency and uncertainty can be addressed by suitable stochastic models in order to estimate the amount of power generated by PV plant. PV power generated is given by:

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_p \left(T_c - T_{c,STC} \right) \right] \tag{1}$$

where P_{PV} is PV output power (kW); Y_{PV} PV rated capacity (kW); f_{PV} derating factor; G_T is incident solar radiation on the solar array (kW/m^2); $G_{T,STC}$ is incident solar radiation under standard test conditions (STC) in (kW/m^2); α_p is coefficient of temperature (%/°C); T_C is solar cell temperature (°C); $T_{C,STC}$ is cell temperature (STC) (25 °C).

Battery charged power (max) is:

$$P_{batt,cmax,mcc} = \frac{N_{batt} I_{\max} V_{nom}}{1000} \tag{2}$$

where N_{batt} is number of batteries; Imax is the storage's maximum charge current (A); V_{nom} is nominal voltage of storage (V).

Net present cost (NPC) is the present cost project life cycle. The objective is to optimize and reduce NPC:

$$NPC = TAC * \frac{\left[(1+i)^n - 1 \right]}{i * (1+i)^n} \tag{3}$$

where *TAC* is total annualized cost ($); *i* is (%) interest rate and *n* is years.

Cost of energy (COE) is average cost/kWh of electricity generated and is:

$$COE = TAC / E_{useful} \tag{4}$$

where E_{useful} is useful production/year (kWh/year).

2.2. Electric vehicles in microgrid

MG system consists of AC load, PV system, EVCS and utility grid as shown in Fig. 2. The objective is to reduce the use of energy imported from the grid and use the PV excess energy to charge EVs. EVs can be treated as energy storage device which can discharge or get charged.

Power balance equation of the MG system is:

$$P_t^{pv} + P_t^G + P_t^{EV,disch} = P_t^{EV,ch} + P_t^L \tag{5}$$

where P_t^{PV} is PV generated power, P_t^G is power imported/exported the grid and P_t^L is the system demand. EVs are treated as an energy storage system which gets charged/discharged.

Power exchanged with the grid is calculated by:

$$P_t^G = P_t^{EV,ch} + P_t^L - P_t^{EV,disch} - P_t^{pv} \tag{6}$$

The charged/discharged power is calculated using:

$$P_t^{EV,ch} = \sum_{k=1}^{N_T} P_k^{EV,ch} \times N_k \tag{7}$$

State of charge (SOC) of EV battery decides either to charge/ discharge

$$SOC_{\min} \leq SOC_{EV,i,k} \leq SOC_{\max} \tag{8}$$

$$SOC_{EV} \leq SOC_{EV,\min} \tag{9}$$

$$SOC_{EV} \geq SOC_{EV,\max} \tag{10}$$

where $SOC_{EV,i,k}$ is SOC of EV battery at *i*th microgrid zone and *k*th location; $SOC_{\min}$ is minimum SOC ; $SOC_{\max}$ is maximum SOC.

3. Site selection

Four Indian cities Shillong, Bengaluru, Jaipur and Kashmir with different solar irradiation are considered for the study as shown in Fig. 3 (Maps of India, 2021).

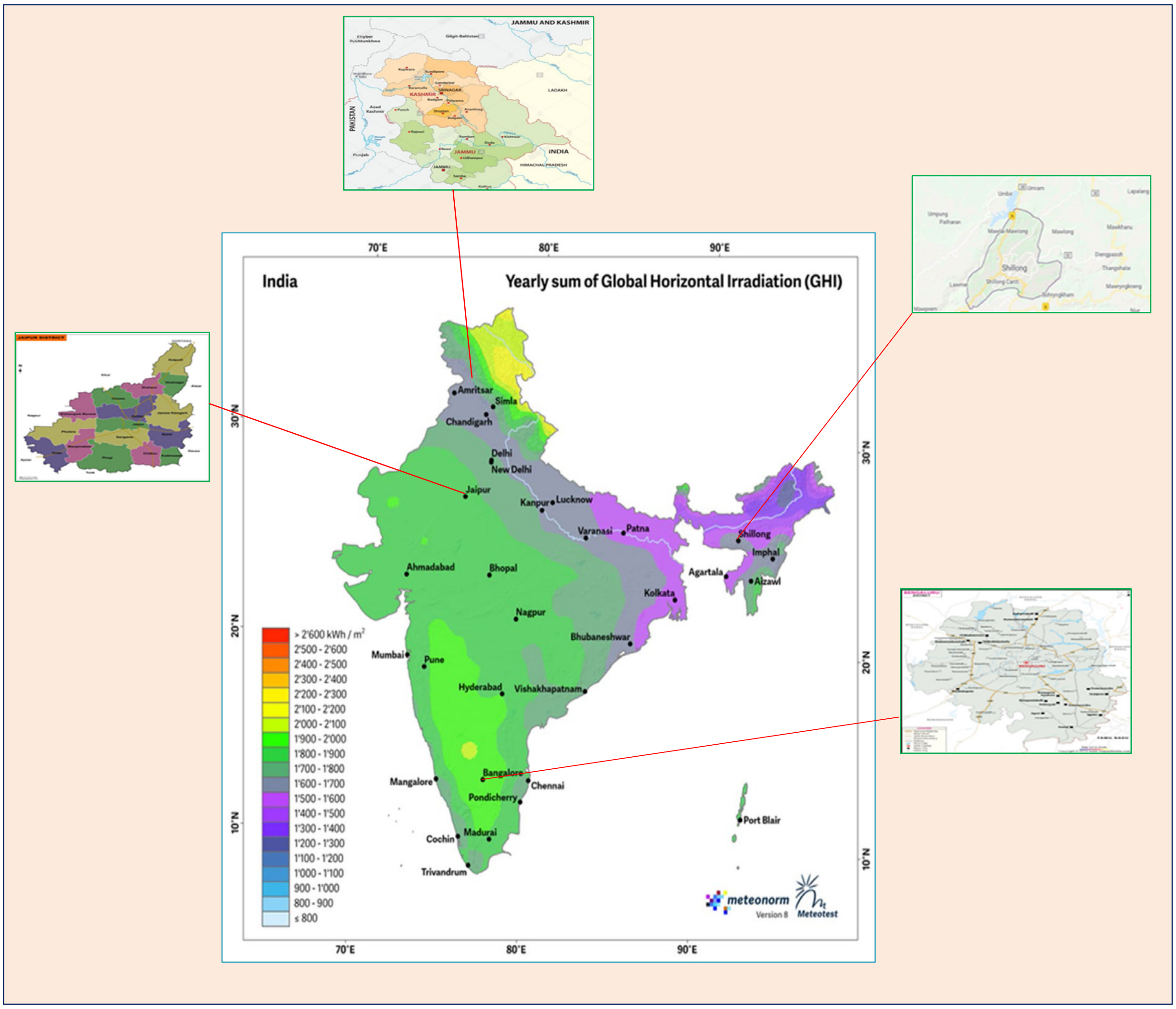


Fig. 3. Solar irradiation map of India.
Source: https://meteonorm.com.

3.1. Shillong city

Shillong is the capital city of Meghalaya, is a hill town, situated in the north eastern India. The serene nature, pleasant climate and pollution free environment attracts tourists from other parts of Indian and abroad throughout the year. It is situated at an altitude of 1496 m above sea level and area is around 64.36 km^2 (24.85 mi^2). Annual average temperature is 18 °C and the most and fewest hours of sunshine is in month of March (monthly average of 249.89 h) and January (monthly average of 219.38 h) respectively contributing to a total of around 2305.11 h of sunshine annually with monthly average of 75.88 h of sunshine. The state Government of Meghalaya is proactive in pushing solar energy initiatives for power generation thereby reducing CO2 emissions and carbon footprints. Average monthly solar radiance of Shillong is shown in Fig. 4. Average monthly solar global horizontal irradiance (GHI) of Shillong is 4.44 kWh/m^2 day (HOMER data) and is shown in Fig. 5. The highest and the lowest irradiation months are March (6.56 kWh/m^2 day) and August (4.47 kWh/m^2 day) respectively.

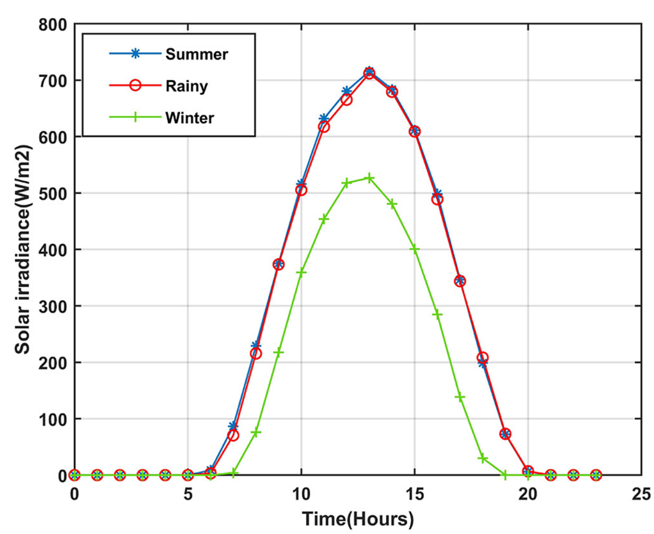


Fig. 4. Monthly average solar radiance (Shillong).

3.2. Bengaluru city

Bengaluru is the capital city of Karnataka and is known Silicon Valley of India. It is also known as garden city of India and is classified as tropical savanna climate as per Köppen climate classification. It has moderate climate throughout the year due to

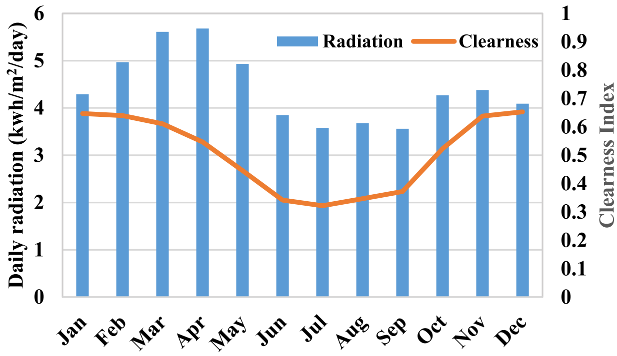


Fig. 5. Monthly average solar GHI (Shillong).

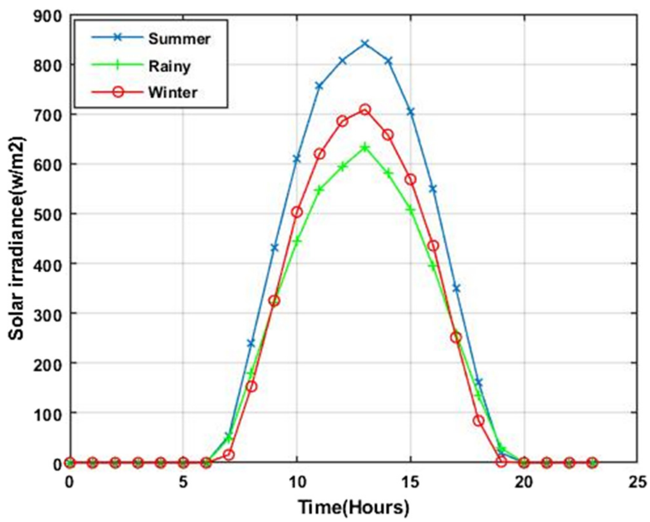


Fig. 6. Monthly average solar radiance (Bengaluru).

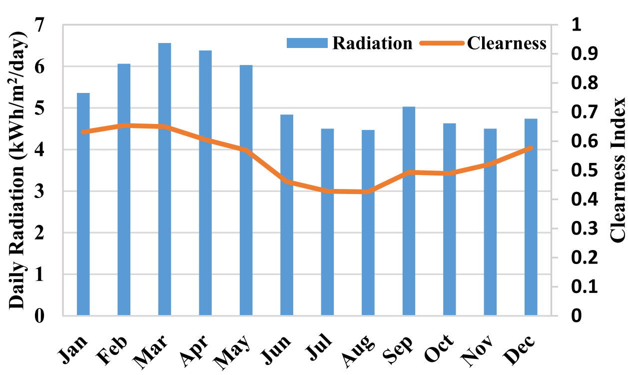


Fig. 7. Monthly average solar GHI (Bengaluru).

its high elevation. The average temperature ranges from 15.1 °C (minimum in the month of January) to 35 °C (maximum in the month of April) and highest ever recorded temperature of Bengaluru city is 39.2 °C on 24th April 2016. The population of Bengaluru is 8.5 million (Census Organization of India 2011). Average monthly solar radiance of Bengaluru is shown in Fig. 6. Solar GHI in Bengaluru is 5.06 kWh/m^2 day(HOMER data) and is shown in Fig. 7. The highest and lowest irradiation months are 6.56 kWh/m^2 day (March) and 4.47 kWh/m^2 day (August) respectively.

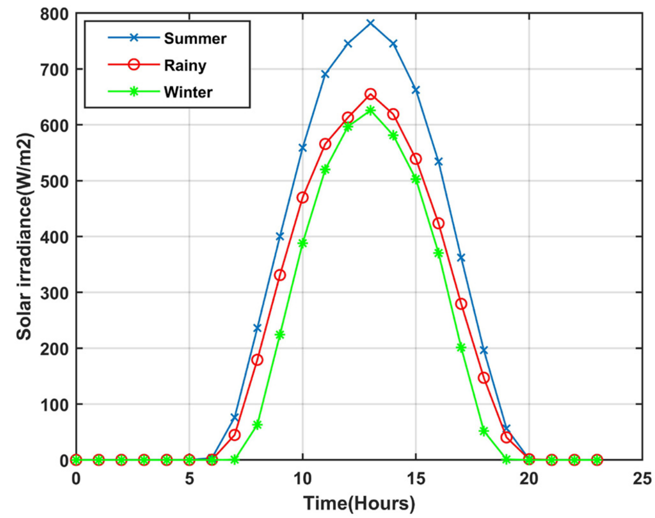


Fig. 8. Monthly average solar radiance (Jaipur).

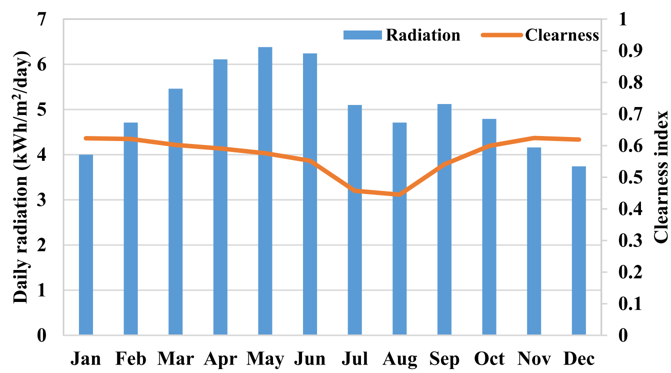


Fig. 9. Monthly average solar GHI (Jaipur).

3.3. Jaipur city

Jaipur is the capital city of North Indian State of Rajasthan and is the largest state constituting to 10.4% geo-graphical area of India. It has a huge solar energy potential and makes it ideal to capture sufficiently the solar rays. Jaipur (Rajasthan) has almost 300–325 sunny days in a year and receives 6–7 kWh/m^2 sun radiation/day and its second highest in the world to record this. Average temperature is between 35 °C to 40 °C and in summer it is above 45 °C. Rajasthan has a solar energy potential of 10000 MW. Average monthly solar radiance of Jaipur is shown in Fig. 8. The highest and lowest solar GHI are 6.46 kWh/m^2/day (month of May) and 4.00 kWh/m^2/day (month of August) respectively with monthly average of 5.26 kWh/ m^2/day in Jaipur as shown in Fig. 9.

3.4. Kashmir city

The state of Jammu and Kashmir is located near the great Himalayan Mountains. Jammu and Kashmir is one of the most beautiful union territories of India. There are four divisions in Jammu, Kashmir Valley and Ladakh amongst which Kashmir Valley is the most urbanized region in the Himalayas. Kashmir has four seasons: Summer (March–May) with temperature not exceeding 30 to 31 °C; Rainy (June–September) with low temperature (9 to 15 °C) and high temperature of 30 °C; Winter (November–February) with temperature as low as sub-zero to high not exceeding 15 °C; Autumn (October–November) with

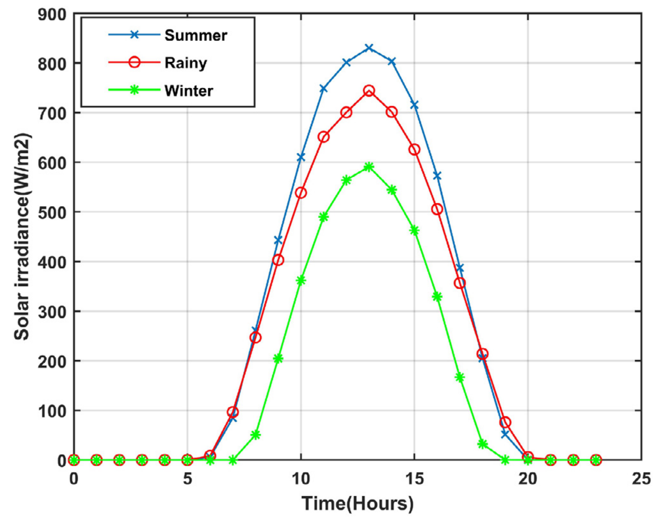


Fig. 10. Monthly average solar radiance (Kashmir).

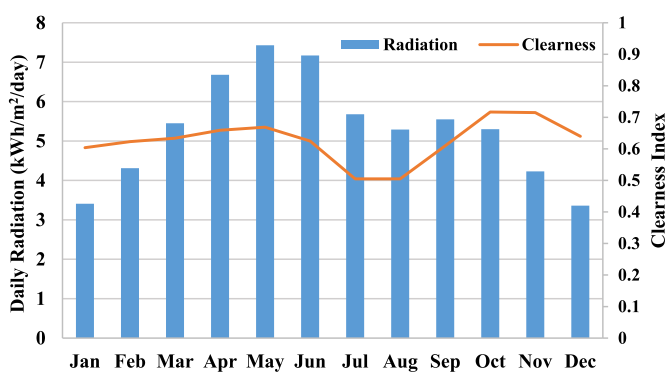


Fig. 11. Monthly average solar GHI (Kashmir).

temperature 9–20 °C. Average monthly solar radiance of Kashmir is shown in Fig. 10. Average monthly solar GHI is 5.32 kWh/m^2 day with highest of 7.43 kWh/m^2 day (month of May) and lowest of 3.36 kWh/m^2 day (month of December) as shown in Fig. 11.

4. Mathematical modeling

4.1. Theoretical demand model

Consider there are n aggregators and m EVs in a Microgrid

Power demand in the time period t is expressed by the following linear function:

$$D(t) = C_1(t) + C_2(t).\, d_p(t) \tag{11}$$

where $d_p(t)$ is the hourly demand price of power at time t ; $D(t)$ is the hourly power demand; $C_1(t)$ *and* $C_2(t)$ are constant coefficients with values > 0

The aggregator has following quadratic cost function given by

$$C_i^A(x_i(t)) = \alpha_i x_{i,t} + \frac{1}{2}\beta_i x_{i,t}^2 \tag{12}$$

where $x_i(t)$ is the amount of electricity generated in the time period t in the aggregator region i;α_i *and* β_i are coefficient constant

Assuming that fleet of EVs connecting to the MG through aggregator either charging/discharging in the time period t at lower prices and higher prices is given by

$$x_{v,t} = -C_{v,t}(d) + C_{v_i,t}(a) + D_{v,t}(a) \tag{13}$$

where $C_{v,t}(d)$ EVs charging for driving in time period t; $C_{v_i,t}(a)$ EVs charging for arbitrage in time period t; $D_{v,t}(a)$ discharging for arbitrage t

Since the linear demand function given by Eq. (11), $D(t)$ satisfies in time period t satisfies

$$D(t) = \sum_{i=1}^{n} x_{i,t} + x_{v,t} \tag{14}$$

Power available at an aggregator is given as

$$P^{avail}(t) = \frac{P_t^{\max}(t) + P_t^{alloc}(t)}{P^{\max}(t)} \tag{15}$$

where $P^{\max}(t)$ maximum capacity of power at time t; $P^{alloc}(t)$ amount of power allocated at time t.

4.2. Mathematical model for EV traffic and resource utilization pattern analysis

EVs act as distributed source or connected load which makes them very apt in addressing the issues related to the time varying load demand. The analysis of EVs traffic and driving pattern are very crucial in assessing the total number of EVs participation in grid transaction The driving pattern is always random and EV arrivals to the MG for charging is stochastic in nature (Hampannavar et al., 2020). EV arrival time depends on the parking space availability in charging station and EV charging mode (leave immediately after expected charge). EV arrival time obeys the normal distribution and its probability density function (PDF) is given by (Li and Li, 2019; Li et al., 2021):

$$f_{IN}(t_{in}) = \left\{ \begin{array}{l} \frac{1}{\sqrt{2\pi}\sigma_{in}}.e^{-\left[\frac{(t_{in}+24-\mu_{in})^2}{2\sigma_{in}^2}\right]};\ 0 < t_{in} < (\mu_{in} - 12) \\ \frac{1}{\sqrt{2\pi}\sigma_{in}}.e^{-\left[\frac{(t_{in}-\mu_{in})^2}{2\sigma_{in}^2}\right]};\ (\mu_{in} - 12) < t_{in} < 24 \end{array} \right\} \tag{16}$$

where t_{in} represents EV arrival rate; σ_{in} and μ_{in} are the standard deviation and the mean value of t_{in}.

The function of EVs arrival and resource availability (charging slot or EV integrator) in MG zone/location 'x' at time t unlike considering parking space in charging slot:

The pattern for resource zone wise is given by

$$O_{x,t}^d = f(N_a(t), R_a(t)) \tag{17}$$

where $N_a(t)$ is total EVs & $R_a(t)$ is average available resource at time t in MG location.

$N_a(t)$ represent the total EVs arrival at time in microgrid zone

$$N_a(t) = \frac{\lambda_i(t)R}{v_i} \tag{18}$$

where $\lambda_i(t)$ v_i and R are EV arrival rate, average speed and the coverage space in microgrid zone i at time t.

$R_a(t)$ is the average number of resources available in microgrid zone i in resource x and time t:

$$R_a(t) = R_{j,x,t}^{Z_{i,avail}} = \sum_j r_{j,x,t}^{Z_{iavail}} P(r_{j,x,t}^{Z_{iavail}}) \tag{19}$$

where $r_{j,x,t}^{Z_{iavail}}$ is % of jth resource in microgrid zone i at resource x in time t.

Dynamic observation is:

$$O_{x,t}^d = N_a(t)\left(\frac{R_a(t) - N_v(t)}{R(t)}\right) \tag{20}$$

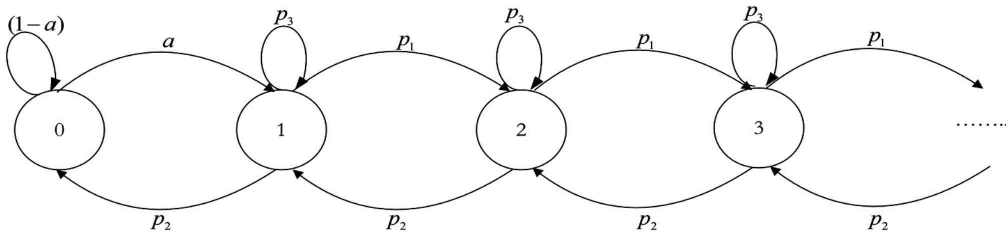


Fig. 12. Markov model for occupancy in MG location.

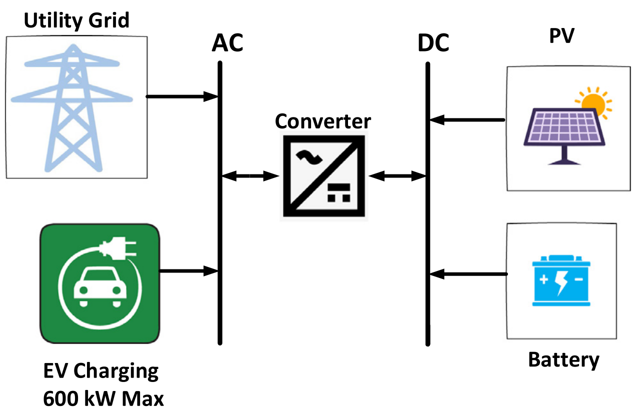


Fig. 13. PV-powered EVCS.

where $R(t)$ is the resources in total available in microgrid zone i

The % of jth resource utility in microgrid zone i at time t is the ratio of allotted actual resources to available resources:

$$U_{x,k}^{PZ_i}(x,t) = \frac{P_{x,daytime/nighttime}^{allocated}}{P_{x,daytime/nighttime}^{avail}} \tag{21}$$

Prediction of jth resource:

$$U_{j,k}^{PZ_i}(x,t) = U_{j,k}^{PZ_i}(x,t) + \max(H_{j,t}^{Z_i} - U_{j,k}^{PZ_i}(x,t), 0) \tag{22}$$

where $H_{j,t}^{Z_i}$ is utilization history of the jth resource.

Poisson's traffic arrival rate with density $\beta isconsideredandthe$ probability of having n EVs in microgrid zone i :

$$p^{Z_i}(n,R) = \frac{(\beta R)^n e^{-\beta R}}{n!} \tag{23}$$

Predicted traffic pattern (growth/ decline) in microgrid zone i at time t:

$$\Delta TV_{x,t,i} = N_{a,x,t}^{Z_i} + p^{Z_i}(n,R) + \max(H_{x,t} - (N^{Z_i} + p^{Z_i}(n,R)), 0) \tag{24}$$

where $N_{a,x,t}^{Z_i} = \frac{\lambda_i(t)R}{v}$

Predicted traffic volume in microgrid zone i is given by

$$\Delta C_{x,t,i} = \frac{1}{|Z_i|}\int_{x=1}^{m} \Delta TV_{x,t,i} dx \tag{25}$$

4.3. Stochastic modeling of EV parking occupancy

EVs arrival in microgrid zone/location for grid integration is random and considered as stochastic problem. Stochastic model using Markov chain is developed for occupancy in microgrid. Let X_n is number of EVs in the microgrid zone at time n, then $X_n \in S := \{0, 1, 2, 3,\ldots, L-1, L\}$ where, n is the charging time slot, L is the location size. EVs arrive at MG zone with a probability a in time slot n. The charging slot of the MG location allocates b for forwarding the EVs and with the probability of $(1-b)$, it is performing task. Stochastic Model for EV occupancy in MG zone is shown in Fig. 12.

EV arrivals/departure influence the state transition: EV arrives at time n, the occupancy is X_n. Similarly, $X_n = X_n$; if there is no arrival in time slot n and $X_{n-1} = X_n$; otherwise. The transition states are presented in Equation.

$$p_{i,j} = \begin{cases} p_1 = a(1-b), & j = i+1, i = 1, 2, \ldots.; \\ p_2 = (1-a)b, & j = i-1, i = 1, 2, \ldots.; \\ p_3 = ab + (1-a)(1-b), & j = i, i = 1, 2, \ldots..; \\ a, & i = 0, j = 1; \\ (1-a), & i = 0, j = 0; \\ 0, & otherwise \end{cases} \tag{26}$$

The probability that all charging slots are busy, so that an arriving message has to join the queue.

5. Components of the solar EV charging station

5.1. Configuration

The structure of the grid connected system consists of PV system, bi-direction converter, utility grid, batteries and EVs as shown in Fig. 13. It is the best suitable model to power EVCS in order to improve the cost of electrical supply and reduce the price of PV system, batteries and carbon footprints. In this EV charging station (EVCS) model, EVs get charged from the PV system during day and grid at night. Excess power generated from PV system can be sold to the grid as per the norms and policies of Ministry of Power (MoP), Govt. of India to support rooftop PV. Batteries in EVCS are designed to meet the power requirements during absence of the PV power and grid power.

5.1.1. Modes of operation of PV-powered EVCS

Mode 1: EV charging from solar PV system alone: EVs in charging station are charged completely by the power generated by PV system . The EVCS will be disconnected from the utility grid.

Mode 2: EV charging from the utility grid alone: EVCS is operated completely by the utility grid because no sunlight or extremely low radiation (cloudy/rainy).

Mode 3: EV charging from both solar PV system and utility grid: If the PV generated power is not enough/sufficient to charge completely then EVs can get charged from both PV system and grid. When the solar irradiation is unstable, the converter has to keep track of maximum power point and support the EVCS.

Mode 4: Selling solar power to the utility grid: When there are no EVs in EVCS to get charged and PV system is generating power then the power generated will be sold to the grid. In this mode, if the power required by EVCS is less than the PV generated power, then the power generated by PV system will be sold to the utility grid.

Mode 5: EV charging from batteries: If PV system is not generating power due to bad weather and grid is unable to supply power

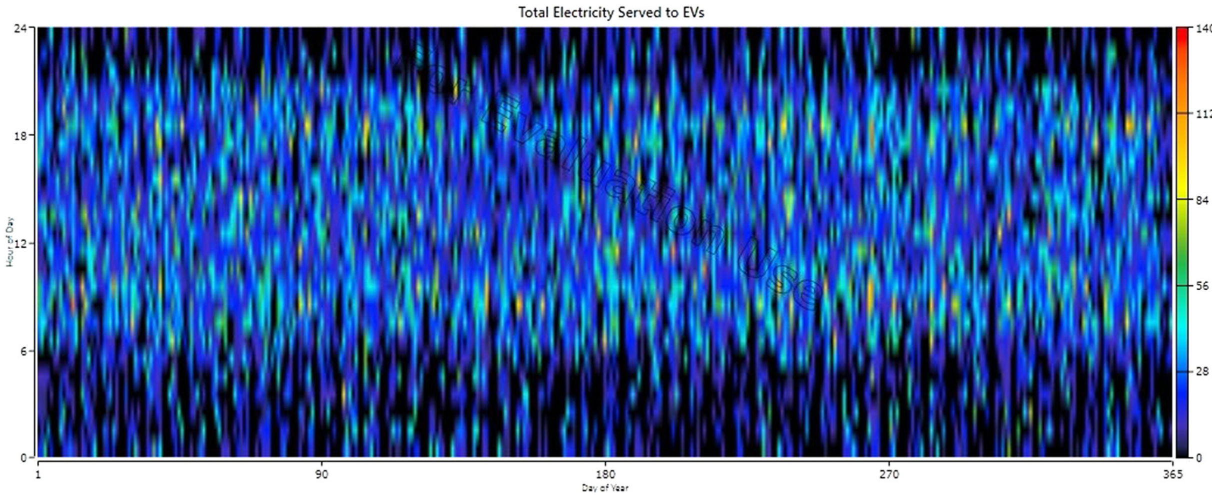


Fig. 14. Annual profile of EV charging.

Table 1
Components.

Component	Size and unit number	Life	Other information
PV system	75, 80, 85,90,95,100 kW	25 years	Derating factor: 80%
Bidirectional Converter	100 kW	10 years	Converter efficiency: 98% Rectifier efficiency: 95%
Utility grid	100 kW		Purchase: 0.104 $/kWh Scenario 1: Sellback: 0.083 $/kWh
Battery	10 units	10 years	Properties per unit: Voltage: 6 V Capacity: 167 Ah
EV charging	Large EV's of 140 kW Small EV's of 50 kW		Max charger output power: 600 kW

Table 2
Cost of supply resources.

Component	Capital cost	Replacement cost	O&M Cost
PV system	750 $/kW	700 $/kW	20 $/kW/year
Bidirectional converter	225 $/kW	200 $/kW	
Lithium battery	550 $/unit	550 $/unit	10 $/unit/year

due to fault then the EVCS can obtain power from battery system. Batteries can get charged themselves from the PV system or grid, but the battery capacity meets the requirement for charging minimum EVs in order to minimize the investment cost.

The components and technical specifications of the PV-powered EVCS in HOMER Grid are listed in Table 1 which includes different values of PV system capacity to find the optimal configuration. Central Electricity Authority (CEA)/ Ministry of Power (MoP) will determine the price of the electricity purchase, by which customer can buy the electricity from the grid at an annual price of about 0.104 $/kWh, while the roof top PV power FIT, while the solar power FIT price is decreasing in recent times (as per the MoP report) and hence in scenario 1 the lowest estimated FIT price of 0.06 $/kWh is considered (see Table 2).

EVCS operating frequency yearly with an average daily charging of 533 kWh/day is shown in Fig. 14. EV daily charging times: Main (8 AM – 5 PM); Other times of the day (6 AM – 7 AM) and lower charging frequency (6 PM–12 midnight).

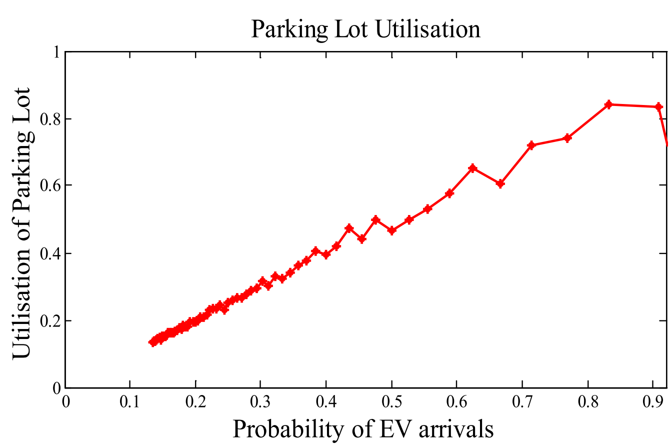


Fig. 15. MG parking utilization.

6. Results and discussion

6.1. Electric vehicles in microgrid

The stochastic model was developed for EVs in queue and parking lot utilization. Simulation were carried out in MATLAB and the results depict that the utilization of the parking lot increases as the probability of EV arrival approaches the value of b as shown in Fig. 15. If the probability of EV arrivals is 0.85 then

Table 3
PV-powered EVCS configuration in Shillong — Scenario 1.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$1,83,883	$0.0614	$6257	$1,03,000	60.6
95	10	1	100	$1,88,329	$0.0645	$6891	$99,250	59.0
90	10	1	100	$1,92,779	$0.0677	$7525	$95,500	57.3
85	10	1	100	$1,97,172	$0.0710	$8155	$91,750	55.5
80	10	1	100	$2,01,529	$0.0744	$8782	$88,000	53.5
75	10	1	100	$2,05,937	$0.0779	$9413	$84,250	51.4

Table 4
PV-powered EVCS configuration in Bengaluru — Scenario 1.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$1,64,857	$0.0528	$4785	$1,03,000	63.6
95	10	1	100	$1,70,286	$0.0560	$5495	$99,250	62.1
90	10	1	100	$1,75,732	$0.0594	$6206	$95,500	60.4
85	10	1	100	$1,81,210	$0.0629	$6920	$91,750	58.7
80	10	1	100	$1,86,705	$0.0667	$7635	$88,000	56.7
75	10	1	100	$1,92,170	$0.0705	$8348	$84,250	54.7

Table 5
PV-powered EVCS configuration in Jaipur — Scenario 1.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$1,59,180	$0.0502	$4346	$1,03,000	64.5
95	10	1	100	$1,64,868	$0.0535	$5076	$99,250	63.0
90	10	1	100	$1,70,672	$0.0569	$5815	$95,500	61.3
85	10	1	100	$1,76,561	$0.0606	$6561	$91,750	59.6
80	10	1	100	$1,82,416	$0.0644	$7303	$88,000	57.7
75	10	1	100	$1,88,119	$0.0683	$8035	$84,250	55.6

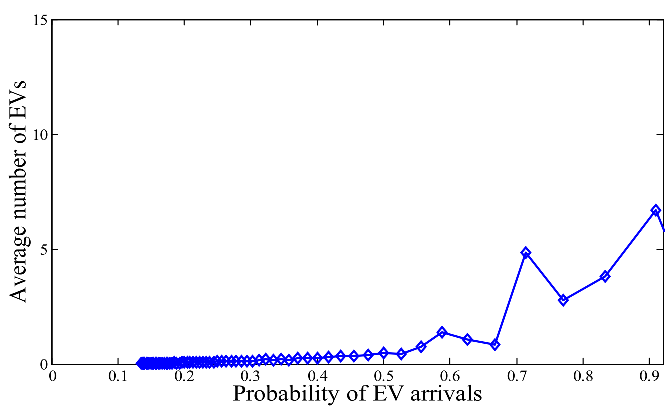


Fig. 16. Backlogs v/s EV arrivals.

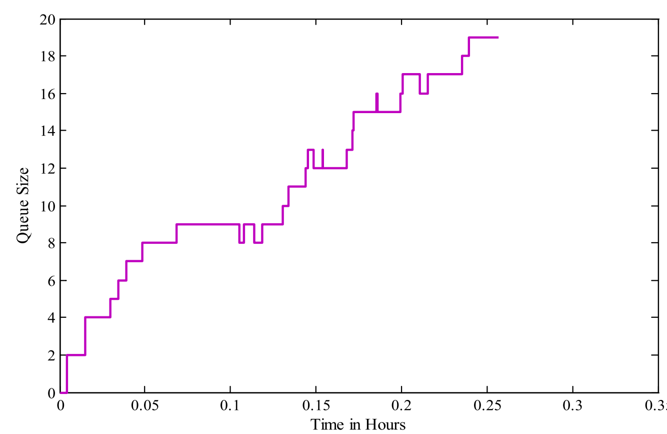


Fig. 17. Queue size for 100 EV arrivals.

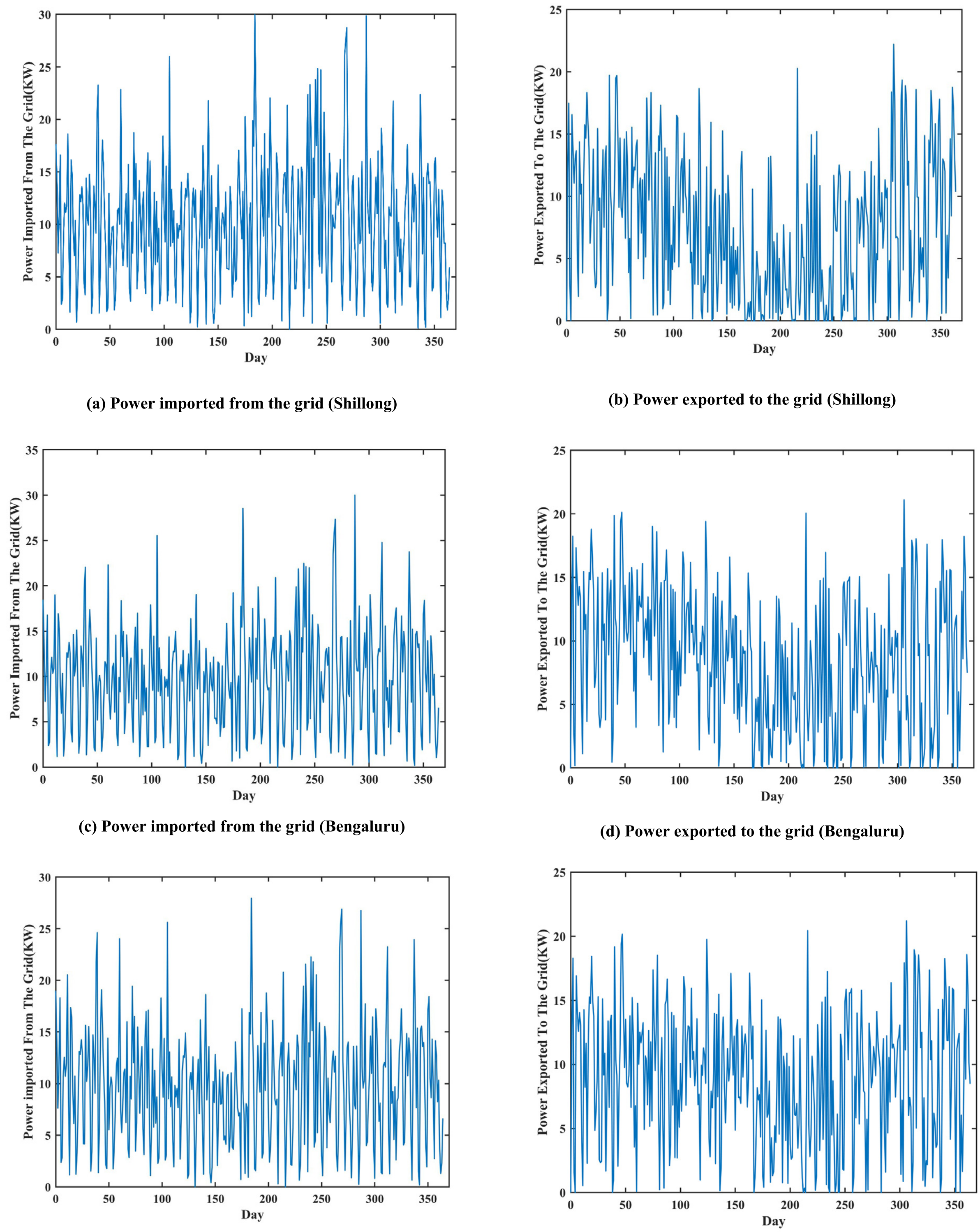
the charging delay in hours is 0.07 h. Fig. 16 demonstrates the number of backlogs increases as the probability of EV increases and Fig. 17 depict the queue size for 100 EV arrivals.

6.2. Scenario 1—Maximum FIT Price is 0.083 $/KWh

The optimal configuration of the PV-powered EVCS located in Shillong (state of Meghalaya), Bengaluru (state of Karnataka), Jaipur (state of Rajasthan) and Kashmir are shown in Tables 3–6 respectively. Maximum PV system capacity of 100 kW is considered to be the most optimal plan because of the lowest NPC value for all four different solar irradiation conditions having same investment cost of $1,03,000 for EVCS.

Power imported/exported to the grid is shown in Fig. 18 and EVCS will use PV power first and if there is deficit of power than will buy from local grid. The cities generating highest PV power: Shillong (January–May & Oct–Dec); Bengaluru and Jaipur (September to May), Kashmir (March–May & September–January).

The ratio of PV power and grid power in the total amount of electricity generated to the EVCS depends on the production power change of the 100 kW PV system and different solar radiation values as listed in Table 7. Shillong has lower solar radiation because of which PV power output of 1,43,702 kWh/year is supplied to the EVCS. Whereas, Bengaluru and Jaipur have relatively greater solar radiation value than Shillong and PV power output of 1,57,421 kWh/year and 1,61,754 kWh/year respectively. Kashmir has highest solar radiation which results in PV power output of 1,76,522 kWh/year and excess power sold back to the grid is 91,820 kWh/year. The excess power sold to the grid are 67,106 kWh/year (Shillong), 77,186 kWh/year (Bengaluru) and 80,512 kWh/year (Jaipur) respectively. Players participating in power



(a) Power imported from the grid (Shillong)

(b) Power exported to the grid (Shillong)

(c) Power imported from the grid (Bengaluru)

(d) Power exported to the grid (Bengaluru)

(e) Power imported from the grid (Jaipur)

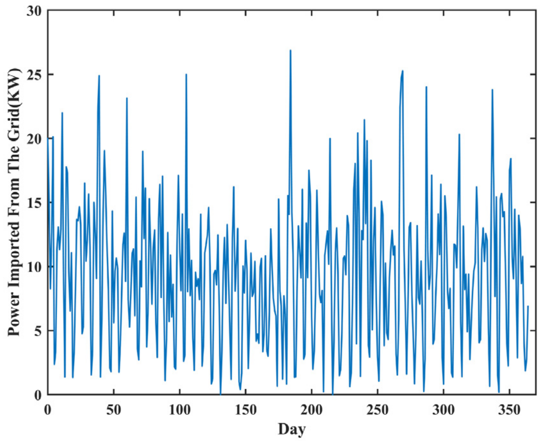
(f) Power exported to the grid (Jaipur)

Fig. 18. Power imported/exported from/to the grid (different cities).

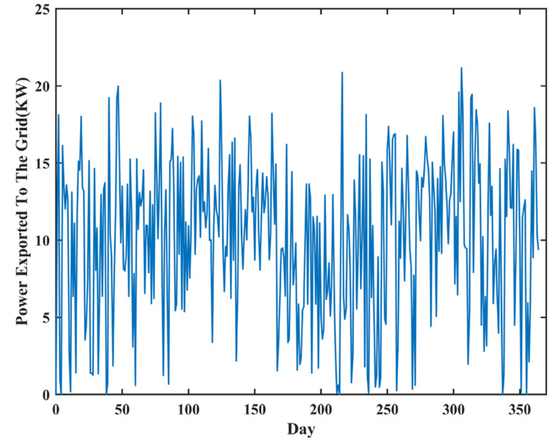
generation can get additional profit by selling excess amount of PV power to the grid.

Fig. 19 depicts the NPC and the operating cost of the PV-powered EVCS in four different cities and it is observed that Kashmir has the lowest NPC and operating cost. Jaipur and Bengaluru have slightly greater NPC and operating cost than Kashmir. Whereas, Shillong has the highest NPC and operating cost.

Fig. 20 portraits the COE of the PV-powered EVCS of four cities of shillong, Bengaluru, Jaipur and Kashmir respectively. It is observed that Shillong has the highest COE of 0.0614 $/kWh; Bengaluru and Jaipur have 0.0528 $/kWh and 0.0502 $/kWh respectively while, Kashmir has the lowest COE of 0.0421 $/kWh. It is interesting to note that COE of all cities is lower than FIT price of 0.104 $/kWh which is encouraging and appreciated by



(g) Power imported from the grid (Kashmir)



(h) Power exported to the grid (Kashmir)

Fig. 18. (*continued*).

Table 6
PV-powered EVCS configuration in Kashmir — Scenario 1.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$1,39,484	$0.0421	$2822	$1,03,000	67.3
95	10	1	100	$1,46,203	$0.0454	$3632	$99,250	65.8
90	10	1	100	$1,53,017	$0.0490	$4449	$95,500	64.3
85	10	1	100	$1,59,927	$0.0528	$5274	$91,750	62.6
80	10	1	100	$1,66,882	$0.0568	$6102	$88,000	60.7
75	10	1	100	$1,73,747	$0.0610	$6923	$84,250	58.7

Table 7
PV-powered EVCS (technical parameter) — Scenario 1.

Content	Shillong	Bengaluru	Jaipur	Kashmir
Solar irradiation (kWh/m^2 day)	4.44	5.02	5.26	5.36
Production				
Optimal PV capacity (kW)	100	100	100	100
PV (kWh/year)	1,43,702	1,57,421	1,61,754	1,76,522
Utility grid (kWh/year)	91,329	87,921	87,001	83,824
Total (kWh/year)	2,35,031	2,45,342	2,48,755	2,60,345
Consumption				
EV charger served (kWh/year)	1,64,563	1,64,563	1,64,563	1,64,563
Grid sales (kWh/year)	67,106	77,186	80,512	91,820
Total (kWh/year)	2,31,669	2,41,750	2,45,076	2,56,384
Renewable fraction (%)	60.6	63.6	64.5	67.3

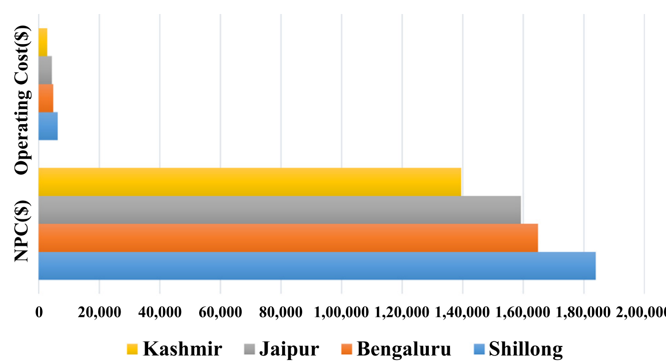


Fig. 19. NPC and the operating cost of the PV-powered EVCS — Scenario 1.

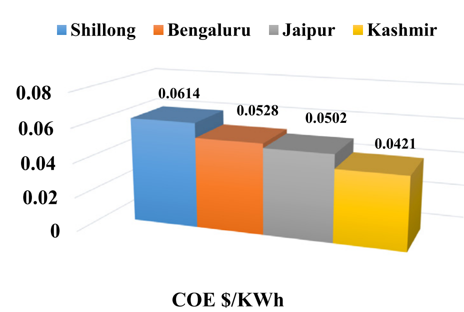


Fig. 20. COE of PV powered EVCS-Scenario 1.

the government authorities. Thus, the investment on PV power EVCS in Kashmir and other parts of India with similar or higher solar radiation is completely feasible. It is inferred that greater the solar radiation smaller is the cost of NPC, COE and operation. So, the investment efficiency of the PV-powered EVCS increases.

6.3. Scenario 2—The Minimum FIT price is 0.06 $/kWh

Tables 8–11 show the optimal system configuration of the PV power EVCS with the FIT price of 0.06 $/kWh for four different cities. Maximum PV system capacity of 100 kW is still the most optimal plan due to the lowest NPC value. If FIT price falls as in scenario 2, the NPC, COE, and operation cost of the solar EVCS will increase slightly as shown in Fig. 21 due to which the investment efficiency of PV-powered EVCS decreases.

In Table 12, the ratio of solar power and grid power in the total amount of generated electricity to the EVCS in all cities in scenario 2 remains the same as in scenario 1.

In Scenario 2, the NPC and the operating cost of the PV-powered EVCS in four cities are shown in Fig. 22. Kashmir has the lowest NPC and operating cost; Bengaluru and Bengaluru are

Table 8
PV-powered EVCS (optimal configuration) in Shillong — Scenario 2.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$2,27,207	$0.0759	$9608	$1,03,000	60.6
95	10	1	100	$2,27,966	$0.0781	$9957	$99,250	59.0
90	10	1	100	$2,28,803	$0.0803	$10,312	$95,500	57.3
85	10	1	100	$2,29,669	$0.0827	$10,669	$91,750	55.5
80	10	1	100	$2,30,614	$0.0851	$11,032	$88,000	53.5
75	10	1	100	$2,31,704	$0.0876	$11,406	$84,250	51.4

Table 9
PV-powered EVCS (optimal configuration) in Bengaluru — Scenario 2.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$2,14,749	$0.0687	$8644	$1,03,000	63.6
95	10	1	100	$2,16,016	$0.0710	$9032	$99,250	62.1
90	10	1	100	$2,17,372	$0.0734	$9427	$95,500	60.4
85	10	1	100	$2,18,832	$0.0760	$9830	$91,750	58.7
80	10	1	100	$2,20,391	$0.0787	$10,241	$88,000	56.7
75	10	1	100	$2,22,028	$0.0815	$10,658	$84,250	54.7

Table 10
PV-powered EVCS (optimal configuration) in Jaipur — Scenario 2.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$2,11,221	$0.0667	$8371	$1,03,000	64.5
95	10	1	100	$2,12,605	$0.0690	$8769	$99,250	63.0
90	10	1	100	$2,14,162	$0.0715	$9179	$95,500	61.3
85	10	1	100	$2,15,864	$0.0741	$9601	$91,750	59.6
80	10	1	100	$2,17,633	$0.0769	$10,028	$88,000	57.7
75	10	1	100	$2,19,374	$0.0797	$10,452	$84,250	55.6

Table 11
PV-powered EVCS (optimal configuration) in Kashmir — Scenario 2.

Architecture				Cost				System
PV (kW)	Battery	Utility grid	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/year)	Initial capital ($)	Renewable fraction (%)
100	10	1	100	$1,98,834	$0.0600	$7413	$1,03,000	67.3
95	10	1	100	$2,00,744	$0.0624	$7851	$99,250	65.8
90	10	1	100	$2,02,800	$0.0649	$8300	$95,500	64.3
85	10	1	100	$2,05,012	$0.0677	$8761	$91,750	62.6
80	10	1	100	$2,07,359	$0.0706	$9233	$88,000	60.7
75	10	1	100	$2,09,722	$0.0737	$9706	$84,250	58.7

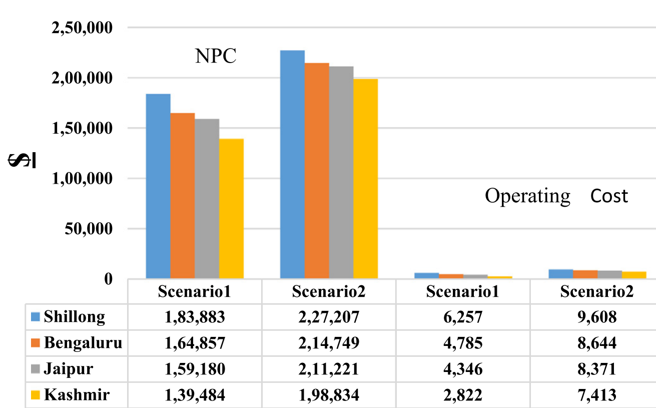


Fig. 21. NPC and the operating cost of the PV powered EVCS (both scenarios).

slightly greater than Kashmir while, Shillong has the highest NPC and operating cost.

For Scenario 2 COE of the PV-powered EVCS for four cities are shown in Fig. 23. It is observed that Shillong has the highest COE of 0.0759 $/kWh; Bengaluru and Jaipur have COE is 0.0687 $/kWh and 0.0667 $/kWh respectively; while Kashmir has the lowest COE of 0.06 $/kWh.

PV-powered EVCS areas having the same solar irradiation with COE equivalent to the solar powered FIT price can also be considered for investing by optimizing the equipment for reduced costs. Shillong has high COE, so it is difficult for investors to make

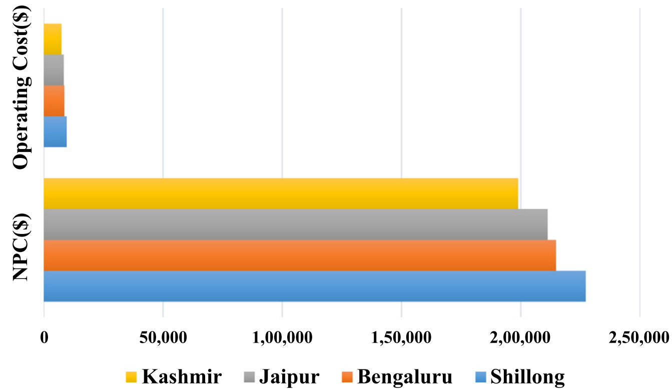


Fig. 22. NPC and the operating cost of the PVpowered EVCS — Scenario 2.

Table 12
Technical parameter of the PV-powered EV charging stations in scenario 2.

Content	Shillong	Bengaluru	Jaipur	Kashmir
Solar irradiation (kWh/m^2 day)	4.44	5.02	5.26	5.36
Production				
Optimal PV capacity (kW)	100	100	100	100
PV (kWh/year)	1,43,702	1,57,421	1,61,754	1,76,522
Utility grid (kWh/year)	91,329	87,921	87,001	83,824
Total (kWh/year)	2,35,031	2,45,342	2,48,755	2,60,345
Consumption				
EV charger served (kWh/year)	1,64,563	1,64,563	1,64,563	1,64,563
Grid sales (kWh/year)	67,106	77,186	80,512	91,820
Total (kWh/year)	2,31,669	2,41,750	2,45,076	2,56,384
Renewable fraction (%)	60.6	63.6	64.5	67.3

profits, the construction of the PV-powered EVCS in the lowest solar radiation areas should be supported by government.

In Minh et al. (2021) EVCS operating frequency is 246 kWh/day and grid purchase: 0.077 \$/kWh for Scenario 1; Sellback: 0.0838 \$/kWh for Scenario 1 and Sellback: 0.08 \$/kWh for Scenario 2. The optimal configuration of the solar powered EVCS in Hanoi, Da Nang, and Ho Chi Minh. The maximum PV system capacity of 50 kW was considered as the most optimal plan due to the lowest NPC value in all three different solar irradiation conditions with the same total investment cost of the solar EV charging station of \$62,550. In this work PV system capacity of 100 kW is considered and from two scenarios it is inferred that it cost effective. Promotion of solar power EVCS is apt for the current situation in India . COE changes of the PV-powered EVCS in four different solar radiation regions with FIT price two scenarios are shown in Fig. 24. Lower the FIT price higher is the COE. PV powered EVCS in Kashmir city can be considered with reduced investment cost because the COE is equal to FIT price in scenario 2. For other cities in scenario 2, COE of the PV-powered EVCS is greater than the new FIT price which indicates that government support for capital investments is absolutely necessary.

It is noted from Tables 7 and 12 that EV charger's consumption is 1,64,563 kWh/year and the CO_2 emissions generated from the utility grid is 1,04,004 kg/year in case of conventional charging (with zero PV). Thus, with the use of PV system with greater capacity in EV charging stations can reduce the rate of grid power usage and the generated amount of CO_2 during the operation process. CO_2 emissions from the PV-powered EV charging stations in different solar radiation regions are shown in Fig. 25. The results present that the generated amount of CO_2 from the EV charging station remains unchanged in both scenarios in all the cities, with 57,694 kg/year, 55,566 kg/year, 54,985 kg/year and 52,977 kg/year, respectively. From Fig. 25 it is observed that CO_2 emissions in Kashmir is less when compared to other cities because Kashmir is having highest solar radiation which means higher the solar radiation lesser the emissions.

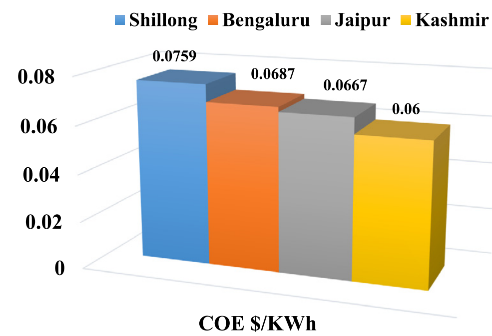
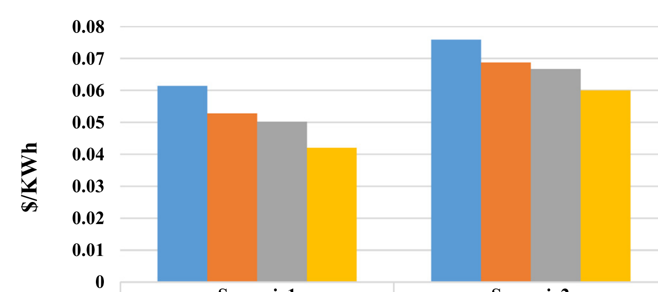


Fig. 23. COE of the PV-powered EVCS — Scenario 2.



	Scenario1	Scenario2
Shillong	0.0614	0.0759
Bengaluru	0.0528	0.0687
Jaipur	0.0502	0.0667
Kashmir	0.0421	0.06

Fig. 24. COE of the PV-powered EVCS for 2-Scenarios.

7. Conclusions

Firstly, stochastic model is developed for EV traffic profile, arrivals and resource utilization pattern. EV parking lot occupancy, EVs in a system and resource utilization in MG zone are presented. Secondly, techno-economic analysis of PV-powered EV charging stations in Microgrid for different solar irradiation conditions in India are discussed comprehensively and optimal system configuration is determined using HOMER grid. It is found from the obtained results that greater the solar irradiation, lesser is the cost of NPC, COE which results in improved investment efficiency for PV power EVCS. It observed that the ratio of PV power and grid power in the total amount of generated electricity for the EVCS remains unchanged for both the scenarios because PV system capacity of 100 kW is still most optimal plan. The more the FIT price falls the COE of two cities will increase slightly

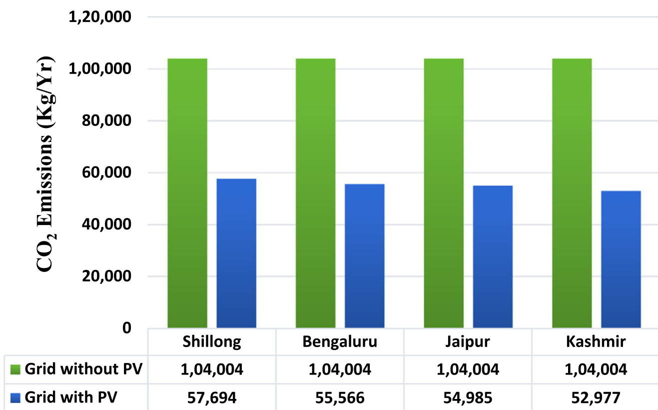


Fig. 25. CO_2 emissions (kg/Yr).

and Kashmir is found to be potential hub for solar power EVCS investment due to high solar irradiation according to both the scenarios.

In scenario 1, COE of Shillong, Bengaluru, Jaipur and Kashmir are 0.0614$/kWh, 0.0528$/kWh, 0.0502 $/kWh and 0.0421 $/kWh respectively and it is possible to invest in the PV powered EVCS by optimizing the equipment in order to reduce total cost of investment. In scenario 2, COE of Shillong, Bengaluru and Jaipur are 0.0759 $/kWh, 0.0687 $/kWh, 0.0667 $/kWh respectively which are higher than the new FIT price. There are different FIT policy options such as long-term policy, payments based on the costs of renewable energy generation, different tariff prices for different technologies, size and location of the project, guaranteed grid access and end user participation. The installation of PV systems with greater capacity in EV charging stations can minimize the amount of generated CO_2 due to its use of grid power. Therefore, this study not only draw the attention of policy makers but also promote the EV industry in India and surrounding countries. So, it is necessary to consider investment possibilities or mobilize capital support from the government or other organizations to build solar powered EVCS. This study not only draw the attention of policy makers but also promote the EV industry in India and surrounding countries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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