Design and Feasibility Analysis of Hybrid Energy-Based Electric Vehicle Charging Station

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Abstract

Mobility has been changing precipitously in recent years. With the increasing number of electric vehicles (EV), travel-sharing continues to grow, and ultimately, autonomous vehicles (AV) move into municipal fleets. These changes require a new, distributed, digitalised energy system, maintenance, and growing electrification in transportation. This paper proposes the designing of an Electric Vehicle Charging Station (EVCS) by using hybrid energy sources such as solar PV, wind, and diesel generator. The proposed system is mathematically modelled and designed using the Hybrid Optimization Model for Multiple Energy Resources (HOMER). The system is analysed and assessed in both autonomous mode and grid-connected mode of operation. The optimum sizing, energy yields of the system in each case is elaborated, and the best configuration is found for design. The variations in Levelized Cost Of the Energy (LCOE), Net Present Cost (NPC), initial cost, and operating cost of the various configuration are presented. From the results, it is observed that the grid-connected EVCS is more economical than the autonomous EVCS. Further, a sensitivity analysis of the EVCS is also performed.

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1 Introduction

Electrification of transportation is one of the main objectives of smart city development. There are two themes in the future transportation system. The first theme represents electrical energy utilisation and decentralisation, and the second theme constitutes autonomous and shared mobility. Figure 1 indicates the convergence of transportation and energy in the future. The objective of electrical energy utilisation is the design of a sustainable EVCS, where a sustainable charging station signifies an infrastructure to charge electric vehicles by using renewable energy sources such as solar PV, Wind, Biomass, etc. The objective of decentralisation is to develop digital infrastructure such as open and real-time automated communication and operations of the energy. The second theme deals with developing a system that takes care of complete driving in autonomous mode. It consists of all street types, traffic, speed, and environmental conditions [1]. The design of the EVCS infrastructure should meet the requirement of the personal use of vehicles. An electric vehicle may be charged at home during evening hours or at destination areas such as car parking, shopping complex, educational institutes, and free parking spaces. The design model of EVCS generally varies with the station maintained and operated by a range of competitors, including public agencies, car manufacturers, energy companies, and pure charging infrastructure players. So, with this motivation and importance, designing of an EVCS based on sustainable energy sources seems to be highly significant for the future transport sector.

The transport sector in India has a significant role in producing GHG emissions. The majority of emissions produced in the transport sector are CO_2. The world energy council observes 17% of GHG emissions being made only from the transportation sector. New developments in technology, policies, and consumer behaviour have the most significant impact on energy consumption in the transport sector. Rapid price reduction is also one of the main reasons for the increasing sales in the electric vehicle sector. As a result, the transport sector experiences growth in energy demand of about 28%. Oil remaining the dominant fuel, a rapid increase in the transportation load affects the environment and increases fuel consumption.

The demand for clean energy applied to the transport sector is growing because high emissions from the internal combustion engine play a crucial

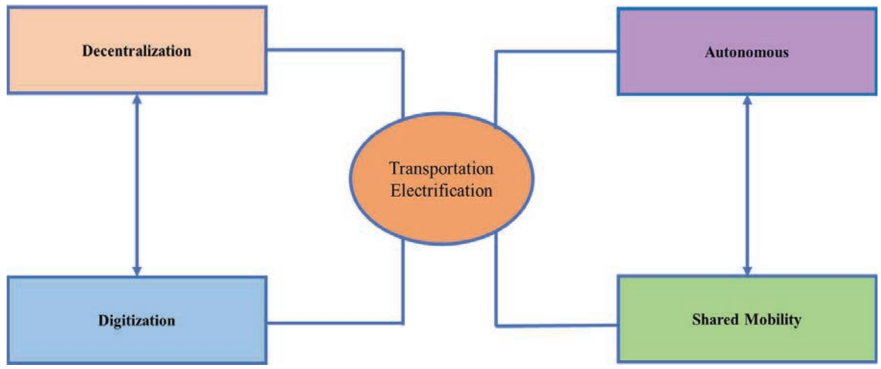

Figure 1 Convergence of transportation and energy in future.

role in air pollutions. There are many other clean energy fuels used for the transport sector, such as biofuels, biodiesel, synthetic fuels, and fuel cells; all this source can be used as a substitute for diesel. The significant sources to generate biodiesel is vegetable oils, fats, and greases are the sources of feed reserves to produce biodiesel. In the transport sector, one more valuable fuel is biofuel; biofuel can be extracted from the various types of biomass products by adopting different technologies and paths which are regularly separated into generators. Synthetic fuels are manufactured from chemical conversion process from carbon sources such as coal, carbon dioxide, natural gas, biogas used for the sources for the transport sector (or) Biomass. The performance of different fuels are analysed, and they were reported [2]. Fuel cell devices, especially proton replacement membrane type, are influential participants to change the internal combustion engines in the transport sector.

One more type of vehicle used for the transport sector is the hybrid electric vehicles. A hybrid electric vehicle (HEV) is a hybrid vehicle that mixes a traditional internal combustion engine (ICE) system with an electric propulsion system. The presence of the electric powertrain is meant to achieve either better fuel economy than a conventional vehicle or better performance [3]. In the transport sector, electric vehicle usage is also increasing slowly. People have started using EVs like auto-rickshaw, Easy bikes, and electric cars. Electric vehicles produce less GHG emissions and no fumes [3].

Many countries have included EVs (Electric Vehicles) in their priority list while formulating transportation policies.Their responses are varied based on economic development, technological capabilities, and availability of energy resources. In India, the opportunity to adopt EVs over ICE (Internal Combustion Engine) vehicles looks very bright due to the enormous abundance of renewable energy sources, availability of skilled labour, infrastructure in the IT and manufacturing sectors. India has taken significant steps in the electrification of vehicles keeping in pace with the global scale. The key objectives of EV policy primarily aim to minimise pollution in cities and to reduce fuel consumption in the transportation sector. These policies are framed to encourage customers to adopt electric and clean energy vehicles, thus facilitating employment growth in the newly equipped auto sector.

As per the sales data estimate, only 2% of automobile sales in India are accounted for premium four-wheelers. It is critical to target the premium customers when it comes to the revolution of automobile electrification. Later, in the long run, the emphasis has to be made on manufacturing economically viable EVs and charging stations to shift the focus onto majority customers, i.e., two-wheelers. The primary agenda to create financially viable EVs is to shorten the number of batteries in an EV and reduce the unit cost of each battery. Businesses that provide battery charging and swapping technology, which are critical parameters to proliferate EVs, are referred to as Energy Operators (EO). The government of India is providing special financial incentives to EO for deploying fast/slow chargers and carrying out battery swapping. Chargers are also referred to as EVSE (EV Supply Equipment). EVSE standards would include safety measures, operational procedures, thermal and humidity levels adhering to globally acceptable standards. The increased penetration of EVs lead to increased energy demand and thus necessitates the need for harnessing renewable energy.

As of May 2020, the power produced from renewable energy sources is significantly less. Figure 2 indicates the percentage of power generated from various sources in India. In India, 62.36% of power is produced from the thermal power plants, but power production from thermal power plants is not an environmentally friendly solution as it harms the ecosystem. In this context, the development of infrastructure for renewable energy sources is essential, which is environmentally friendly and produces less Green House Gases (GHG) emissions as compared to other conventional sources. The objective of the Ministry of New Renewable Energy (MNRE) is to install 175 GW of power generation from renewable energy sources by 2022. To meet the mission of MNRE, it is necessary to develop the infrastructure required to tap the untapped non-conventional energy sources such as solar, Wind, Biomass, etc. Hence, hybrid energy-based EVCS is necessary for transportation electrification [4, 5].

The optimum system modeled by using Biomass, solar PV, and grid integration were tested by using three different algorithms, namely, HOMER

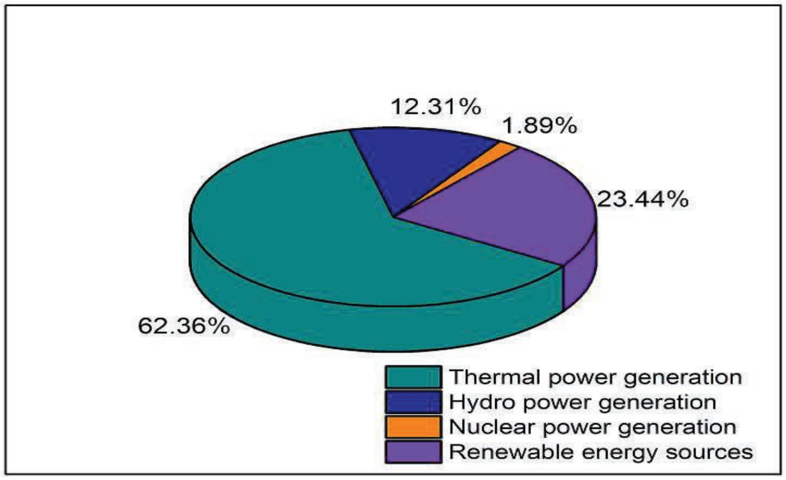

Figure 2 Power generation from different sources.

pro, bee colony algorithm, and P&O. The parameters obtained from all the algorithms were compared, and the variation found was very minimal. From this, it is also concluded that a grid-connected hybrid energy system gives better results than the autonomous system in terms of LCOE and NPC [6, 7]. Another feasibility study was conducted in South Ghana for a stand-alone hybrid energy system by using HOMER pro with the help of solar PV, Wind, and diesel generator. In this study, the comparison was made between two systems, namely PV-Wind-DG-Battery and wind-DG-battery systems. The results obtained from the study concluded that the unit cost is higher than the current cost of the energy of household consumers in Ghana. Another objective assessed in this case study is a sensitivity analysis of the project. In a sensitivity analysis, the effect of fuel cost, inflation rate, and discount rates were considered to study the impact on the project feasibility [8]. Another project was executed based on HOMER pro in the western ghats region of South India for a village load application. The system was designed using Biomass, solar-PV, and pico-Hydel energy [9].

An electric vehicle charging station feasibility study was conducted using the hybrid energy system such as Biomass and solar PV in Bangladesh. The feasibility study was carried out with the help of HOMER pro [10]. The system was verified in terms of technical, economical, and eco-friendly conditions, and the system was found to be more feasible for electric vehicle charging applications. Several hybrid energy system analyses were reported in optimum sizing, a techno-economic assessment of the community, commercial and industrial load applications. These studies were based on the autonomous mode of operation [11–21]. Designing and utilising hybrid energy-based EVCS using solar PV, Wind in both grid-connected and autonomous mode is not attempted so far in any part of India. The main objectives of the proposed research are the following.

(1) To develop a novel model for an EVCS using hybrid energy sources.
(2) To perform optimum sizing and techno-economic analysis of the proposed system.
(3) To analyse the proposed system in both grid-connected mode of operation and autonomous mode of operation.

1.1 Methodology Adopted

The proposed methodology is represented in Figure 3. The methodology for the design of EVCS is divided into different parts. The first step is to assess the potential of solar and wind resources. The resource assessment is performed based on the data received from NASA and a physical survey. The electrical vehicle load is estimated based on the number of vehicles available, hours of charge required, and daily and monthly energy demand requirements. The proposed system is mathematically modelled in terms of technically and economically. The technical parameters consist of the optimum sizing of the solar PV, wind, converter, and sizing of the battery. In the economic assessment, the parameters like total cost of each component, the net present cost of the system, LCOE, profitable index, and a payback period are assessed. The mathematical modelling for the proposed approach is carried out using the HOMER Pro software. The HOMER Pro software uses the solar, wind resources data from the US National Aeronautics and Space Administration (NASA).

To assess the feasibility of the system, the following condition is considered. If the proposed system's LCOE is less than the grid LCOE and the profitable index is greater than unity, then the EVCS is economical; otherwise, EVCS is not economical for the design. If the GHG emission produced by the charging station is higher than the grid emissions, the developed model shall not be feasible. If the power produced from the EVCS is more than the power required for EVs charging, the excess power is exported to the grid. If the power produced by the EVCS is not sufficient for the EVs charging, power is imported from the grid. The EVs can be charged for 8–10 hours per day. The charging hours of EVs depend upon their state of charge (SOC) value.

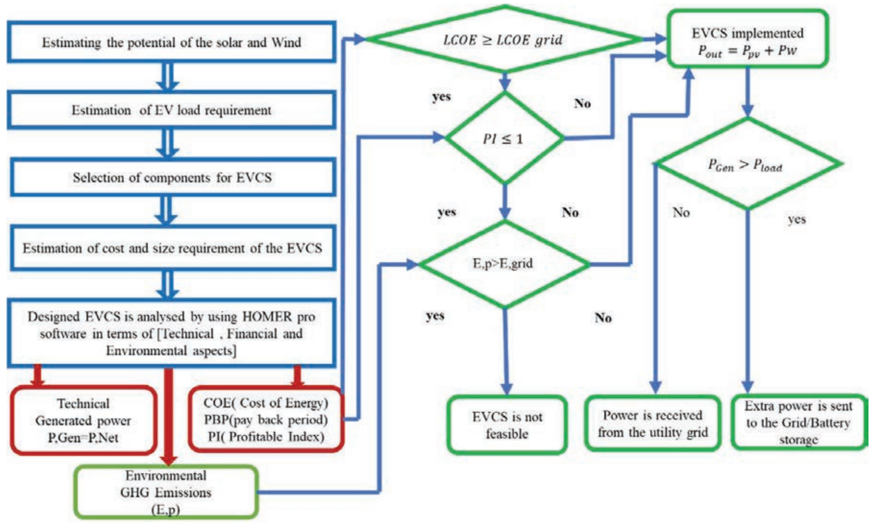

Figure 3 Proposed methodology for the design of EVCS.

2 Schematic Diagram and Mathematical Modelling of the Proposed System

The proposed model is designed to operate in two modes of operation, namely, autonomous mode and grid-connected mode. Figures 4 and 5 demonstrate the modelling of the proposed EVCS in the autonomous and grid-connected modes of operation. The proposed model consists of a solar PV system, wind turbine, diesel generators and battery storage. Since the load is working with AC supply, it is necessary to convert the generated DC power into AC power, and the inverter is connected between the solar PV and the AC loads. The lead-acid batteries are used for storing the excess power generated from the sources during the autonomous mode of operation.

2.1 Modelling of Proposed System Architecture Using HOMER

A typical simulation in a HOMER software is shown in Figure 6 as a flowchart. Primarily the proposed system is mathematically modelled and estimated the EVCS load requirement, type of resources, resources availability in that particular location, technical specifications of each component, project economics and project limitations. HOMER optimization algorithm is used to select the best configuration for the design and to perform project techno-economic performance assessment. The sensitivity analysis is

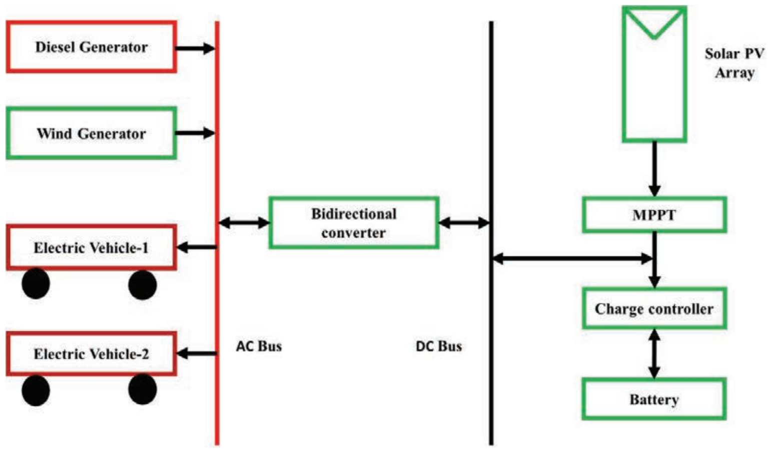

Figure 4 Autonomous mode EVCS.

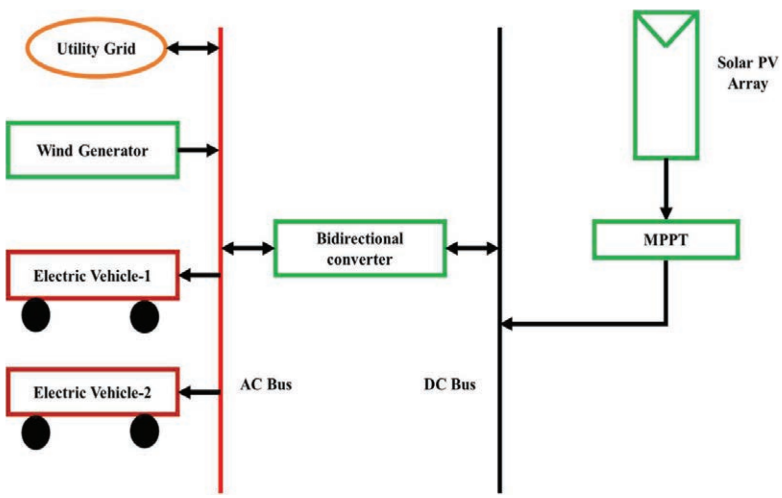

Figure 5 Grid-connected mode EVCS.

a unique simulation environment in HOMER that allows for predicting the future of microgrid projects for an unforeseen circumstance.

2.1.1 Solar array

The solar PV module consists of a photovoltaic cell that converts radiation into electrical energy. The output power can be assessed based on the equations and module specifications as given by the manufacturer. The output of

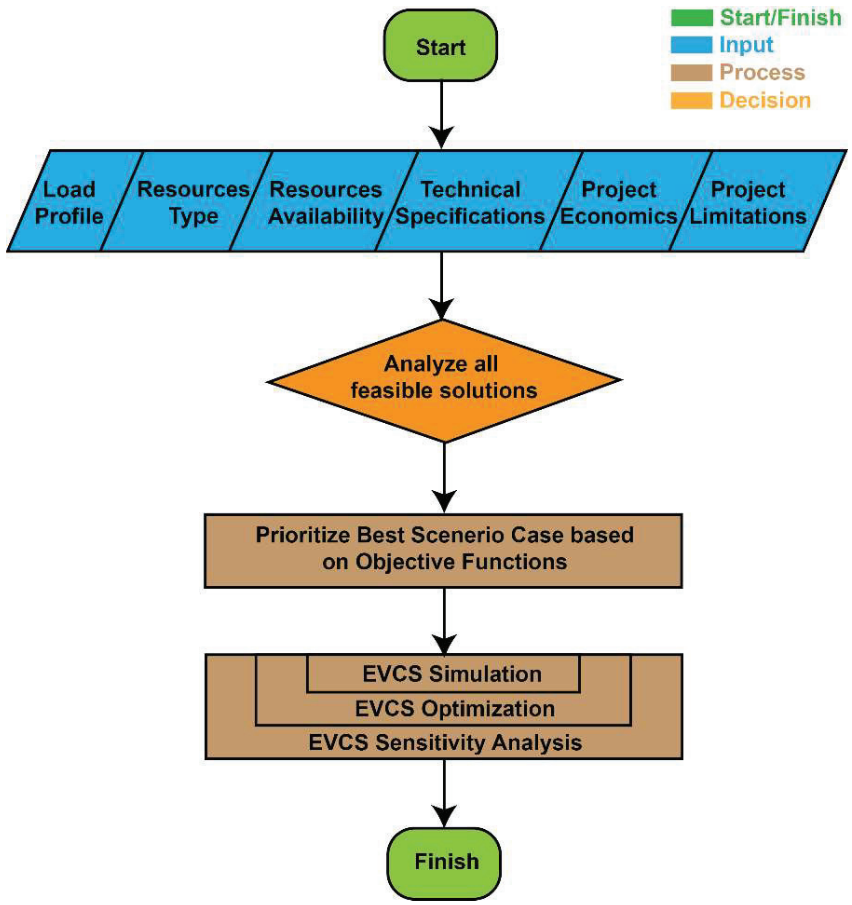

Figure 6 Flowchart to arrive at the optimal system using HOMER software.

the module depends upon the input irradiance and temperature. It is assumed that the output power is proportional to the input irradiance. The output power for the PV module can be calculated using Equation (1) [22, 23].

$$P_{Sol^{(t)=P_{rat}}} f_{loss} \frac{G_h}{G_s}[1 + \alpha_p(T_C - T_s)] \tag{1}$$

P_{rat} represents the solar power output capacity of the solar PV panel; f_{loss} represents the loss of the solar panel. Loss factor includes the losses due to partial shading, temperature, and drift. G_h indicates hourly solar incident radiation on solar panel (W/m^2). G_s indicates standard incident irradiation

(1000 W/m^2), α_p is the temperature coefficient of the power, T_c is the current cell temperature in the current step, and T_s is the PV cell temperature under STC.

2.1.2 Wind turbine

The output power of the wind turbines mainly depends upon the speed of the wind. The quadratic model can calculate the output power produced by the wind turbine by using Equation (2).

$$\mathrm{P_w(V_v)} = \left\{ P_n \frac{v_v^2 - v_d^2}{v_n^2 - v_d^2} \right\},\ \mathrm{V_d < V_v < V_n}$$

$$\mathrm{P_{n,}V_n \leq V_v < V_c 0, V_v \leq V_d et V_v \geq V_c} \tag{2}$$

where P_w represents the output power produced by the wind turbine, P_n indicates the nominal power, V_d is the cut-in speed of the wind, V_v indicates the cut off speed of the wind, and V_n is the rated wind speed.

$$\frac{V(z)}{V(z_a)} = \left(\frac{z}{z_a} \right)^{\propto} \tag{3}$$

To assess the power developed by the wind turbine, it is necessary to calculate the wind speed. The wind speed for specific high is calculated using Equation (3).

2.1.3 Utility grid

In the grid integrated mode, if the power generated by the hybrid energy system is more than the load requirements, the excess power generated is sent to the utility grid. The power supplied to the grid is calculated by using Equation (4).

$$\mathrm{P_{gs}(t)} = [\mathrm{P_{pv}(t)}\eta_{\mathrm{inv}} + \mathrm{P_w(V_v)(t)}] - \mathrm{P_L(t)} \tag{4}$$

If the power generated by the system is not sufficient, and power is drawn from the grid, the amount of power drawn from the grid is calculated by using Equation (5).

$$\mathrm{P_{gp}(t)} = \mathrm{P_L(t)} - [\mathrm{P_{pv}(t)}\eta_{\mathrm{inv}} + \mathrm{P_w(V_v)(t)}] \tag{5}$$

2.1.4 Power demand of the electric vehicle

Power consumed by the electric vehicle depends upon three factors, namely, distance travelled, battery capacity, and mode of driving. Power consumed by the electric vehicle can be calculated by using Equation (6)

$$P_C = \frac{K_d.E_k}{T} \tag{6}$$

where K_d indicates the number of kilometers driven, E_k indicates the energy necessary to drive the vehicle, and T is the time required to charge the vehicle. T is the difference between the departure and arrival time of the charging station. The time needed to charge the vehicle depends on the SOC of the battery. Power consumed by the electric vehicle can be assessed by using battery capacity, SOC, and its charging time, Equation (7) is used for the calculation of power consumed by the EVs.

$$P_C = \frac{Q_{batch} \times (SOC_{max} - SOC)}{T} \tag{7}$$

where Q_{batch} indicates battery capacity and SOC_{max} indicates the upper limit of SOC, and T is the charging duration.

The power demand of the N_{th} electric vehicle can be calculated using Equation (8)

$$P = \sum_{i=1}^{N} P_C \tag{8}$$

2.1.5 Battery modelling

Two types of batteries are to be considered while designing a charging station. One of them is the battery in electric vehicles, and the other the one used for storing the excess power generated during the autonomous mode of operation. Generally, the charging time and the charging rate of the battery depends on SOC. The charging status of the battery can be described either in terms of SOC or (Dept of Discharge) DOD of the battery. Suppose the battery is fully charged, then the SOC of the battery is 100%. If the battery is fully discharged, then its DOD is 100%. For a better life cycle of the battery, a 100% DOD situation should be avoided. While estimating the power requirement of the proposed charging station, SOC is considered as 20%, and DOD is considered as 80%.

The energy required by the battery can be calculated by using Equation (9).

$$Q_{Battery} = SOC + \int_0^t V_{bat} I_{bat} dt \tag{9}$$

where SOC indicates the initial value of the charge of the battery.

The SOC of the battery can be estimated by using Equation (10)

$$B_{SOC} = \frac{Q}{Q_{bat.max}} \times 100\% \tag{10}$$

2.1.6 Power inverter

The power generated by the solar PV panel is DC. Since the load works with AC supply, it is necessary to convert the generated DC power into AC power. An inverter is used for converting DC power into AC power with a constant frequency with inbuilt MPPT. The amount of power the inverter can convert depends upon the rating of the inverter used. The rating inverter can be calculated by using Equation (11) [24, 25].

$$\mathrm{P_{inv}(t) = P_{pv}(t)}\eta_{\mathrm{inv}} \tag{11}$$

where $P_{pv}(t)$ represents the total output power of the PV system, and η_{inv} indicates inverter efficiency.

$$\mathrm{P_{pv}(t) = P_{sol}(t)N_{sol}} \tag{12}$$

$P_{sol}(t)$ indicates the power generated from a single solar PV cell, and N_{sol} represents the number of solar PV panels. In an integrated grid system, the size of the inverter depends on grid sale capacity and local load demand.

$$\mathrm{P_{max.inv} = P_{L.max}(t) + P_{gs.max}} \tag{13}$$

where $P_{L.max}$ (t) represents the maximum load demand, and $P_{gs.max}$ indicates the maximum amount of power sold to the grid.

2.1.7 Electric vehicles

The objective of NITT (National institute of technology Tiruchirappalli, India) is to incorporate sustainability in the transport sector. To achieve this objective, NITT has implemented an application-specific innovative approach in vehicle designing by procuring EVs. The two types of EVs exclusively utilised for on-campus transportation are TE-S14 and E3210 Shaktivahan (E-Rickshaw). Both are used for the transportation of people. TE-S14 is a fourteen seater vehicle in which DC shunt motor is used as the electric drive. A DC-DC converter controls the speed of the DC motor according to the requirement. The available AC supply in the charging station is converted to DC using a diode bridge rectifier, and the output is fed to the batteries. The vehicle is designed with twelve units of 6 V Trojan batteries in series with a total voltage rating of 72 V. The output of the batteries is connected to a DC-DC converter. The motor used for the designing TE-S14 vehicle is rated with 72 V, 6.3 KW rating.

The technology used for E-3210 vehicle is more advanced than that used for the TE-S14 vehicle. The electric drive circuit used for the E-3210 is Brush Less DC Motor (BLDC). The BLDC is an advanced electrical machine used for the electrical vehicle application [26]. There are many advantages in the BLDC drive compared with the standard DC motor drives. In a typical DC motor, the commutation takes place mechanically with the help of a commutator, but in the BLDC motor drive, commutation takes place electronically, without commutator. The rating of the machine used for the designing of E-3210 is 1000 W, 48 V BLDC motor. The battery used for the design of EV is 12 V, 100 AH. The number of batteries used for the vehicle is four, total voltage rating of the battery is 48 V. E-Rickshaw can be used to transport four people at a time. The maximum speed of the vehicle is 25 Kmph. Depending upon the rating of the EVs and the measured data, the load requirement is estimated for 24 hours. To meet the load requirement from renewable energy sources, EVCS is designed with the help of hybrid renewable energy sources.

2.2 Economical Analysis

The objective of this section is to verify the economic feasibility of the model, and another objective is a minimization of the total cost of the proposed system.

2.2.1 Levelized cost of energy (LCOE)

The LCOE is defined as the ratio of the sum of the entire cost collected during the project lifespan to the number of kWh generated over the entire lifetime of the project [27–31]. The LCOE of the selected model can be calculated by using Equation (14)

$$\text{LCOE} = \left(\sum_{i=0}^{T} \left[\frac{C_i + L_i + O\ \&\ M_i + I_i}{(1+d)^i} \right] \right) \Bigg/ \left(\sum_{i=0}^{T} \left[\frac{E_i}{(1+d)^1} \right] \right) \tag{14}$$

where C_i represents the system cost, L_i indicates the cost of the land, $O\&M_i$ is the entire operation and maintenance, I_i indicates annual insurance cost during the project lifetime T, and d is the discount rate. The LCOE determined is useful for the investor to invest in hybrid energy system projects.

2.2.2 Net present cost (NPC)

It is defined as the present value of the total cost of the system throughout the project lifetime minus the present value of the total revenue during the project lifetime. The NPC of each component of the system and the overall cost of the system is calculated by using Equation (15). In this work, the opted system is based on the minimum total net present cost (NPC).

$$\text{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{15}$$

Here $\mathrm{C_{ann.tot}}$ indicates the total annualised cost, i is the total annual interest rate, CRF (i, N) is the capital recovery factor, which is calculated by Equation (16) $\mathrm{R_{proj}}$ is the life of the project, and N represents the number of years.

$$\mathrm{CRF_{(i,N)}} = \mathrm{i(1+i)^n/((1+i)^{(n-1)}} \tag{16}$$

2.2.3 Expected payback period (EPP)

The payback period of a project is one of the critical parameters for investing in the project. The payback period indicates that the project will be profitable on completion of the payback period, EPP can be calculated using Equation (17).

$$EPP = \frac{\sum C_c + C_{O\&M} + C_{Rep}}{C_{cash} flow} \tag{17}$$

where C_c indicates the capital cost of the project, $C_{O\&M}$ indicates the operation maintenance cost of the project.

2.2.4 Annualized capital cost

The capital cost of the hybrid energy system includes the cost of the component and installation cost. For example, the annualized capital cost of the wind türbine can be calculated by using Equation (18)

$$C_{ACC}^{WT} = C_{Cap}^{WT} CRF(i, n) \tag{18}$$

C_{Cap}^{WT} is the initial cost of the wind türbine, where CRF indicates the capital recovery factor, n indicates lifetime, i indicates interest rates.

2.2.5 Annualized replacement cost

The replacement cost is defined as the cost of the replacement at the end of the lifetime of the component. For example, the replacement cost of the wind türbine can be calculated by using (19)

$$C_{Arep}^{WT} = C_{rep}^{WT}\mathrm{CRF(i, n)}\frac{1}{(1+i)^{y}} \tag{19}$$

C_{rep}^{WT} indicates the replacement cost, y indicates the lifetime of the türbine in years.

2.2.6 Salvage value

It is defined as the value remaining of a component at the end of the project life. For example, wind türbine salvage cost can be calculated by using Equation (20)

$$C_{Sal}^{WT} = C_{rep}^{WT}\frac{R_{return}}{N_{wind.1}} \tag{20}$$

C_{rep}^{WT} Indicates the replacement cost, R_{return} indicates the remaining life cycle of the wind türbine, and $N_{\mathrm{wind.1}}$ indicates the life span of the wind turbine.

2.2.7 Profitable index for the project

Profitable Index (PI) plays a significant role in the execution of any project. It indicates whether investors can invest in the project or not. As per PI, if the profitable index is greater than 1, the project is profitable and the project can be executed further; but if PI is less than 1, then the project shall be rejected, and reframing of the modelling is necessary for such type of projects.

PI can be calculated by using Equation (21).

$$PI = \frac{T.C_{cashinflow}}{\sum C_{cap} + C_{O}\&M + C_{Repl}} \tag{21}$$

where T indicates the lifetime of the project in years

$$PI = \frac{T}{EPP} \tag{22}$$

3 Resource Utilisation and Selection of Components

The NITT, located at coordinates of $10^{0}45.7$ N latitude and $78^{0}48.5$ E longitude in Tiruchirappalli, India, is considered for the project implementation. The solar and wind resources for this location are taken from NASA. It is found that the daily average solar irradiation for the location is 5.233

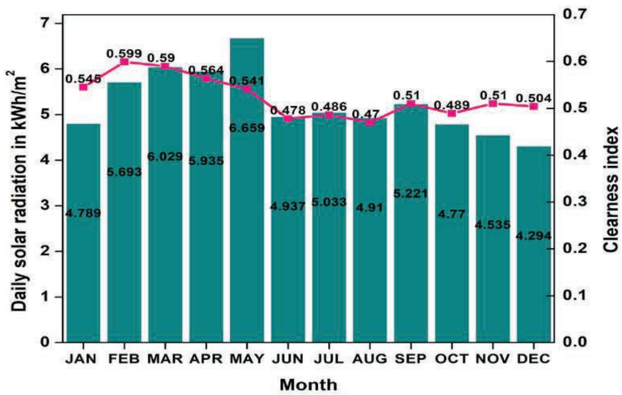

Figure 7 Monthly average solar irradiation and clearness index.

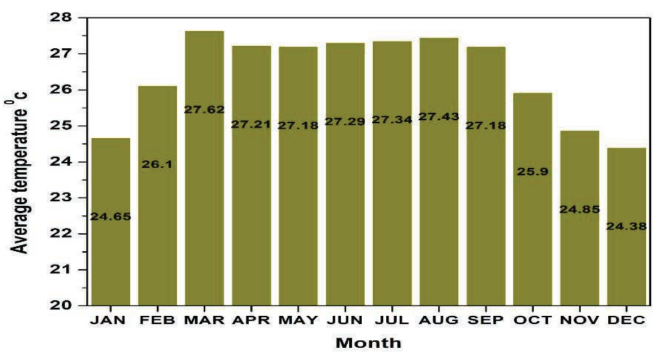

Figure 8 Monthly average temperature variation.

kWh/m^2/day. The variation of daily average solar irradiation and clearness index with respect to months are presented in Figure 7. The monthly average temperature variation is presented in Figure 8. It is estimated that approximately the location receives an average wind speed of 3.40 m/s. The monthly average speed variation is demonstrated in Figure 9. This case study is modelled assuming the lifetime of the project to be 25 years. The cost of energy purchased from the grid is fixed as 0.1 \$/kWh, and the cost of energy sold to the grid is fixed as 0.15 \$/kWh.

4 Results and Discussions

The performance of the proposed model has been analysed in both grid-connected mode and autonomous mode of operation.

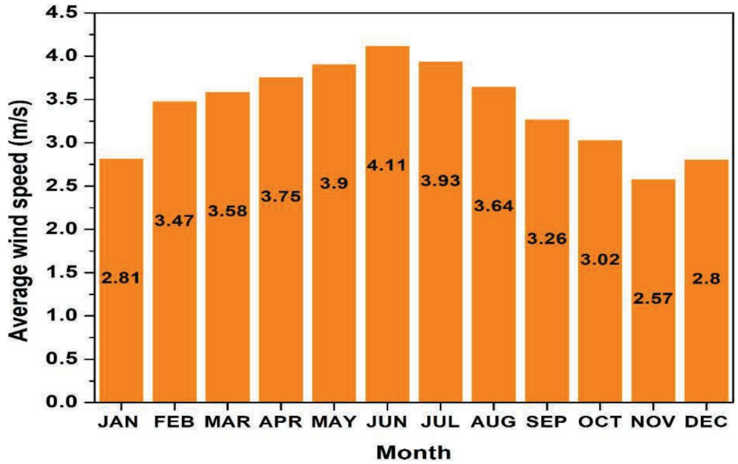

Figure 9 Monthly average wind speed variation.

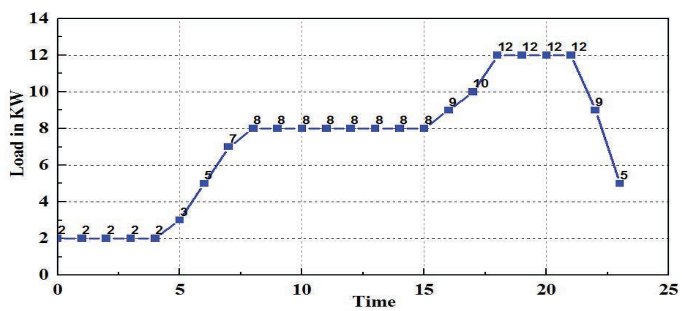

Figure 10 Daily Load variation of EVCS.

4.1 Autonomous Mode of Operation

In the autonomous mode, solar PV, wind, diesel generator, and batteries are used to run the EVCS. The daily load variation is represented in Figure.10. Daily energy demand is estimated at 164 kWh. The time taken to charge the battery is entirely depending on the SOC of the EVs battery.

The performance of the proposed system is analysed in two different cases. In case-1, all the sources are active such as solar PV, Wind, and diesel generator, and in case-2 solar PV and a diesel generator is active, the optimum results obtained are presented in Figures 11 and 12. In case-1, the energy produced from solar PV, wind turbine, and a diesel generator is 63.73%, 0.65%, and 35.62%, respectively. Whereas in case-2, solar-PV produces 64%, and diesel generator produces 36% of the total energy. Table 1 represents the

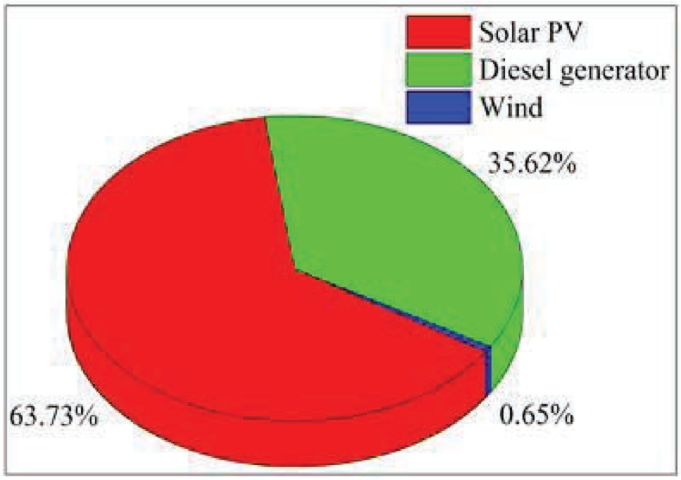

Figure 11 Solar PV, Wind, and DG are active.

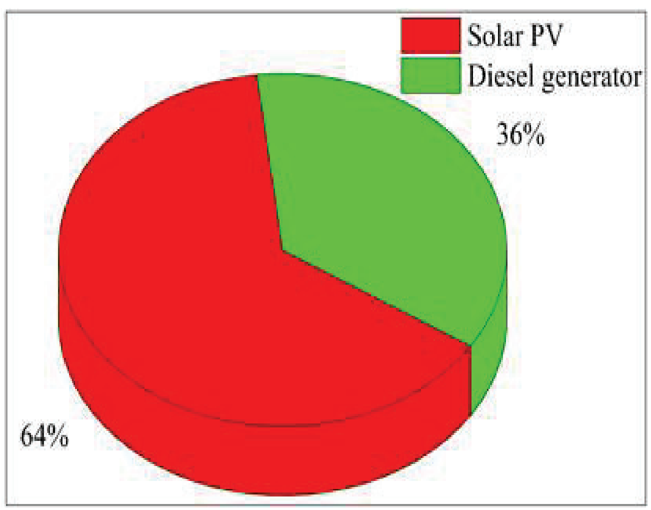

Figure 12 Solar PV and diesel generator active.

comparison between all two cases. The LCOE, NPC, OC and initial cost of the case-1 are estimated as 0.336 $/kWh, $506503, $16173, and $102181 respectively. Whereas in case-2, 'the LCOE, NPC, OC and initial cost of the system are estimated at 0.320 $/kWh, $483115, $15898 and $85668. It is observed that case-2 is more optimum than the case-1 in terms of sizing and economic operation of the system.

Table 1 Comparison of different case studies

Case Study	Active Sources	Sizing of the Sources	LCOE in $	NPC in $	OC in $	Initial Cost in $	Payback Period	PI
Case-1	Solar PV+DG+ Wind	Solar PV-30KW DG-10KW Wind-3KW LA-147 string	0.336	506503	16173	102181	4.418	>1
Case-2	Solar PV+DG	Solar PV-30KW DG-10KW LA-152 String	0.320	483115	15893	85668	3.911	>1

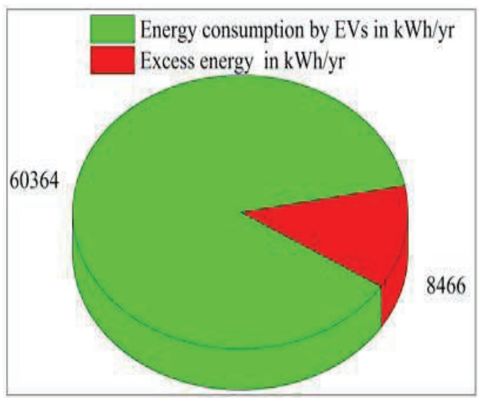

Figure 13 Case-1 (Solar PV, Wind, and DG).

4.1.1 Energy consumed by the EVs during the autonomous mode of operation

Energy consumed by the EVCS during the autonomous mode of operation is represented in Figures 13 and 14. In case-1, when all three sources are active, the annual energy consumed by the EVCS is estimated as 60364 kWh/yr, and the annual excess energy available is 8466 kWh/yr. Similarly, in case-2, when solar PV and DG alone active, the energy consumed by the EVCS is 60364 kWh/yr, but the excess energy available is 8071 kWh/yr.

In the autonomous mode, to store excess power generated during a light load condition, lead-acid batteries are installed. Since both the sources of solar and wind are unreliable, it is necessary to have sufficient storage to run

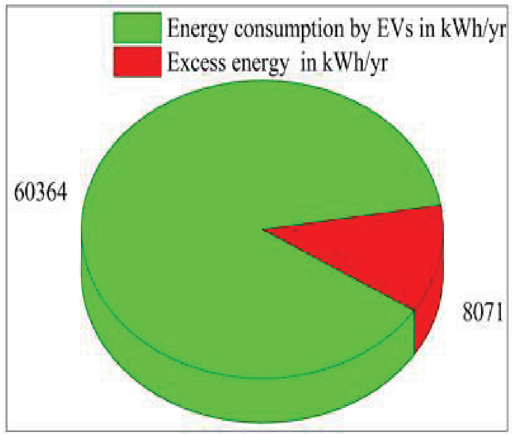

Figure 14 Case-2 (Solar PV and DG).

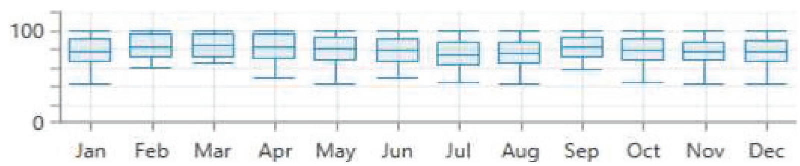

Figure 15 Monthly SOC of the battery.

the system when energy production is not available. Figure 15 represents the variation of SOC of battery in each month. February, March, and April record the least battery charging. This condition can be possible in two cases, either enough power generation is not available, or high discharge occurs during the period. The reason for low power generation is due to the unfavorable conditions of solar irradiation and wind speed. In February, March, and April, there is high irradiation, but the temperature recorded is also high due to the negative temperature coefficient of the semiconductor, which may be the reason for low energy production. Due to the high temperature, the yields of the Solar PV reduced. Figure 16 indicates the SOC of the battery for 365 days.

4.2 Sensitivity Analysis of System

In the sensitivity analysis, the effect of inflation, discount rate, and fuel cost on the project are analysed. Figure 17 indicates the effect of fuel cost on the project. HOMER performs the optimisation of the system by considering each variable. In this case, fuel cost is considered as 1 $/L, 1.5 $/L. When the

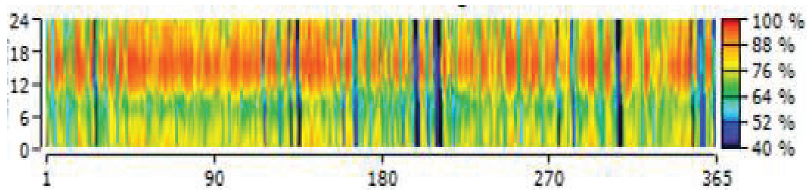

Figure 16 Yearly SOC of the battery.

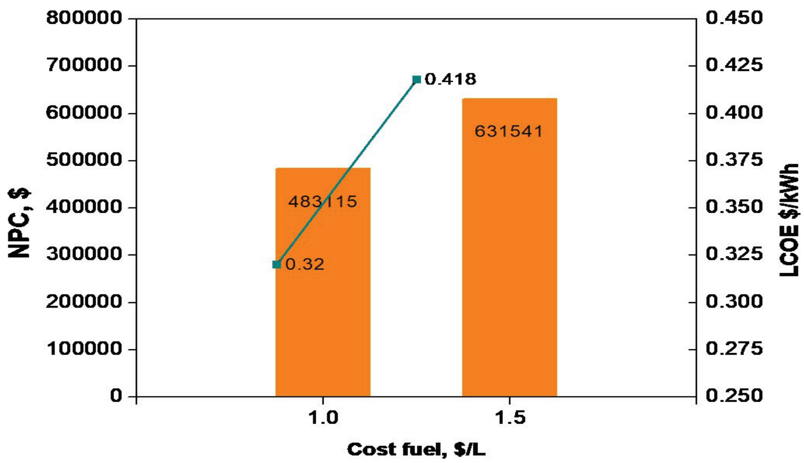

Figure 17 Effect of fuel cost variation on LCOE and NPC.

fuel cost increases, LCOE and NPC also increase. The increasing fuel cost will affect the payback period and performance index of the project.

Similarly, the effect of inflation on the project is assessed. The percentage of inflation rates are considered as 2%, 4%, 6% and 8%. As the inflation rate of the system increases, LCOE reduces, and NPC increases. Figure 18 indicates the effect of the inflation rate on LCOE and NPC.

Similarly, the effect of discount rates on the project is assessed. In Figure 19, it is observed that, as the discount rates increase, the NPC value of the project comes down, but the value of LCOE increases. Tables 2 and 3 indicates the summary of EVCS in autonomous mode.

4.3 Grid-Connected Mode of Operation

In the grid-connected mode of operation, two cases are considered to check the feasibility of the system. In case-1, all the sources are active such as solar PV, wind, and grid in case-2 solar PV alone is active, and the system

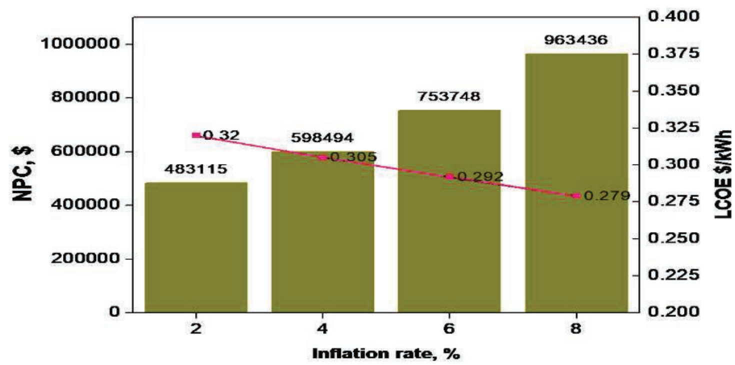

Figure 18 Effect of inflation rate on LCOE and NPC.

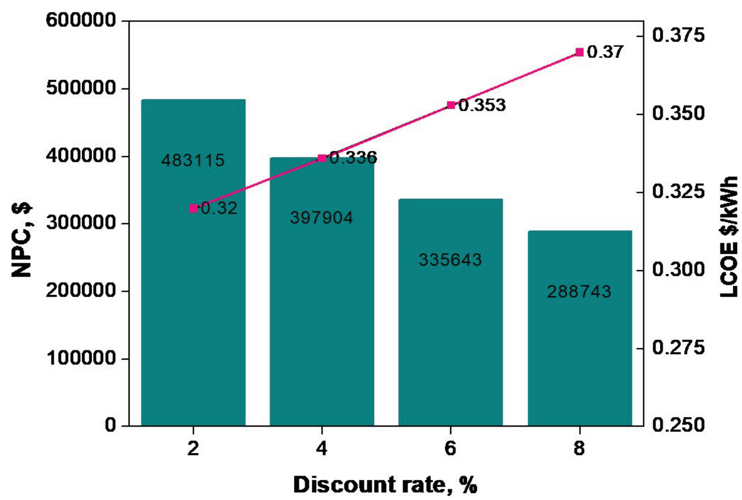

Figure 19 Effect of discount rate on LCOE and NPC.

is integrated into the grid. Optimum results obtained are presented in the Figures 20 and 21. In case-1 annual energy produced from solar PV is 56.81%, and the energy produced from the wind generator is 0.58%. The energy imported from the grid is 42.61%. In case-1, LCOE, NPC, operating costs, and initial costs are assessed as 0.0451 $/kWh, $90042, $1340 and $56535. Tables 4 and 5 indicates the monthly energy production and the energy sold to the grid. In case-2, the energy produced from the solar PV is 57%, and imported from the grid is 43%. The LCOE, NPC, OC, and the initial cost are assessed as 0.0324 $/kWh, $64475, $1038, and $38535. It is

Table 2 Summary of EVCS cost in autonomous mode (When Solar PV and DG is active)

Component	Capital Cost in $	Replacement in $	O&M in $	Fuel Cost in $	Salvage Cost in $	Total in $
Generator 10kW	2780	16680	30840	234339.49	(407.73)	284231.76
Solar PV 30 kW	36000	0	7500	0	0	43500
Battery 1 kWh (152 numbers)	45600	91200	38000	0	(22636.64)	152163.36
Power modulator	1287.86	2575.73	0	0	(643.93)	3219.66
System	85667.86	110455.73	76340	234339.49	(23688.31)	483114.78

Table 3 Summary of EVCS cost in autonomous mode (When Solar PV, Wind and DG is active)

Component	Capital Cost in $	Replacement in $	O&M in $	Fuel Cost in $	Salvage Cost in $	Total in $
Generator 10kW	2780	16680	30817.50	233456.08	(421.63)	283311.95
Solar PV 30 kW	36000	0	7500	0	0	43500
Wind 3 KW	18000	18000	4500	0	13500	27000
Battery 1 kWh (147 numbers)	44100	88200	36750	0	(19610.22)	149439.78
Power modulator	1300	2601	0	0	(650.25)	3251.25
System	102180.50	125481	79567.50	233456.08	(34182.11)	506502.97

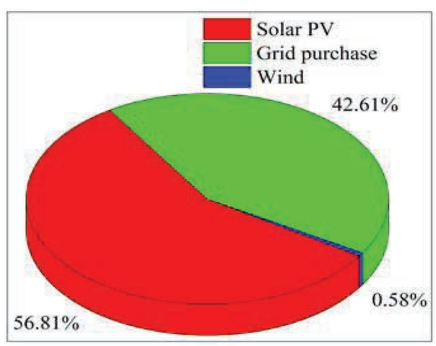

Figure 20 Solar PV and wind are active.

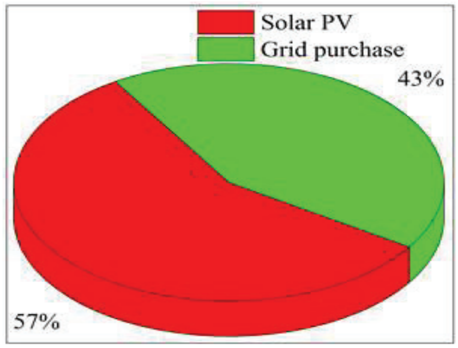

Figure 21 Solar PV alone active.

Table 4 Energy produced and energy sold to the grid when both Solar PV, Wind, and DG are active

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Energy Charges ($)
JAN	3,067	1,758	1,310	$43.11
FEB	2,465	1,970	495	−$49.02
MAR	2,765	2,344	421	−$75.06
APR	2,718	1,859	858	−$7.11
MAY	2,741	1,755	987	$10.93
JUN	2,811	1,364	1,448	$76.58
JUL	2,891	1,328	1,563	$89.85
AUG	3,072	1,441	1,630	$90.96
SEP	2,881	1,681	1,200	$35.97
OCT	2,928	1,349	1,579	$90.46
NOV	3,107	1,286	1,821	$117.73
DEC	3,123	1,390	1,733	$103.78
Annual	34,569	19,525	15,044	$528.17

observed that case-2 is more optimum in terms of sizing and economic point of view.

Annual energy consumed by the electric vehicle charging station and the energy exported to the grid is presented in Figures 22 and 23. Figure 22 indicates when both solar PV and wind generators are active, and both are generating, during this period, energy consumed by the charging station is 60386 kWh/yr and the energy exported to the grid is 19525 kWh/yr, and

Table 5 Energy produced and energy sold to the grid when Solar PV alone is active

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Energy Charges ($)
JAN	3,076	1,752	1,324	$44.80
FEB	2,481	1,951	530	−$44.56
MAR	2,788	2,323	465	−$69.59
APR	2,739	1,829	910	−$0.416
MAY	2,780	1,729	1,051	$18.60
JUN	2,862	1,336	1,525	$85.72
JUL	2,929	1,301	1,628	$97.71
AUG	3,097	1,419	1,678	$96.82
SEP	2,895	1,667	1,228	$39.47
OCT	2,940	1,341	1,599	$92.83
NOV	3,112	1,283	1,829	$118.78
DEC	3,133	1,386	1,747	$105.36
Annual	34,831	19,318	15,514	$585.51

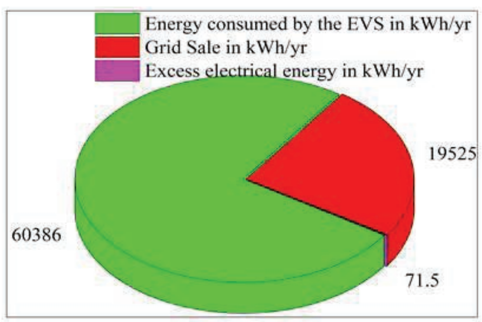

Figure 22 Energy consumed of EVs and grid export.

the excess available energy is 71.5 kWh/yr. Figure 22 indicates the solar PV is active, and the system is grid integrated. In this mode of operation, the total energy consumed by the EVCS is the same as the previous case, 60386 kWh/yr, but the energy exported to the grid is 19318 kWh/yr, and the excess energy available during this case is estimated as 71.5 kWh/yr.

Table 6 represents the economic comparison between both the cases solar-PV, wind, grid, and Solar-PV-Grid. When the comparison is made between Case-1 and Case-2, case-2 is more feasible. LCOE, NPC, and the initial cost of the system are very minimal in case-2 compared with case-1. Table 6

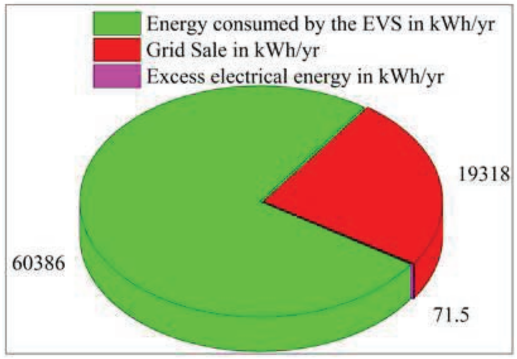

Figure 23 Energy consumed by EVs and grid export.

Table 6 Cost variation by varying the system architecture

Architecture of the System	NPC in $	COE in $	Operating Cost in $	Initial Capital in $
Case-1 Solar PV-Wind-Grid	90041.5	0.045	1340.26	56535
Case-2 Solar PV-Grid	64475.09	0.03236	1037.61	38535

Table 7 Summary of the proposed system cost (Solar PV is alone active)

Components	Capital Cost in ($)	Replacement Cost in ($)	O&M Cost in ($)	Salvage Cost in ($)	Total ($)
Converter	2534.90	5069.79	0	(1267.45)	6337.24
Solar PV	36000	0	7500	0	43500
Grid	0	0	14637.84	0	14637.84
System	38534.90	5069.79	22137.4	(1267.45)	64475.80

indicates the cost variation of case-1 and case-2. From the comparison, it is concluded that case-2 is more economical than case-1. Tables 7 and 8 indicates the cost summary of both case-1 and case-2.

4.3.1 Greenhouse gases (GHG) mitigation

The amount of GHG emissions that can be reduced with the operation of hybrid energy systems for conventional power generation is known as GHG mitigation. In India, almost 62.8% of electrical energy generation is attributed to thermal power generating stations. Thermal power plants liberate enormous amounts of GHG emissions (carbon dioxide, sulfur dioxide, and nitrous oxides) into the environment. Generation of one unit (kWh) electrical

Table 8 Summary of the proposed system cost (Solar PV and Wind is active)

Components	Capital ($)	Replacement ($)	O&M ($)	Salvage($)	Total ($)
Converter	2534.90	5069.79	0	(1267.45)	6337.24
Solar PV	36000	0	7500	0	43500
Grid	0	0	13204.26	0	13204.26
Wind	18000	18000	4500	(13500)	27000
System	56534.90	23069.79	25204.26	14767.45	90041.50

Table 9 Comparison of the present system with the existing literatüre

Type of Hybrid Energy Sources	LCOE in $/kWh	NPC in $	Initial Cost in $	Mode of Operation	Reference
PV+Wind+DG + Battery	0.382	8.65 million	880103	Autonmous	[18]
Wind+DG+Battery	0.396	8.97 million	804750	Autonmous	[18]
PV+Biomass	0.349	609524	–	Autonmous	[17]
PV+Biomass+DG	0.366	639796	–	Autonmous	[17]
PV+Biomass	0.118	205499	–	Grid connceted mode	[17]
PV+Wind+DG	**0.336**	**506503**	**102181**	**Autonmous**	**Present system**
PV+DG	**0.326**	**483115**	**85668**	**Autonmous**	**Present system**
PV+Wind	**0.045**	**90041.5**	**56535**	**Grid connceted mode**	**Present system**
PV	**0.0323**	**64475.09**	**38535**	**Grid-connected mode**	**Present system**

energy from thermal power plants produces 980 g of carbon dioxide [32, 33], 1.24 g of sulfur dioxide, 2.59 g of nitrogen oxide, and 68 g of ash .Generating adequate power from hybrid renewable sources reduces GHG emissions into the environment and can minimize environmental hazards wiz global warming, ozone layer depletion, etc. GHG mitigation for the autonomous and grid connected mode of operation is calculated when only solar is active(Best optimum result case is considered) is resultant of 45172.12 kg of C_{O2}, 57.15 kg of S_{O2} 119.38 kg of N_{OX}.

Table 9 represents the comparison between a present system with the existing literatüre; from the comparison, it is found that the present model is more optimum in terms of sizing and economic point of view. The LCOE, NPC, and initial cost of the project significantly less comparing that of existing models.

5 Conclusions

Detailed design and techno-economic performance assessment of the hybrid energy-based EVCS has been presented based on the result obtained from the HOMER simulator and real-time measured data from the EVs. The proposed EVCS is mathematically modelled, simulated, and the techno-economic performance of the charging station is assessed. The EVCS is designed for both grid-connected mode and autonomous mode of operation, and the optimum result obtained is presented.

- In the autonomous mode, the LCOE, NPC, and operating cost is estimated at 0.326 $/kWh, $483115, and $85668, while in grid connected mode LCOE, NPC, and operating cost is estimated at 0.0323 $/kWh, $64475.09 and $38535.
- The optimum sizing of the sources and energy produced to charge the EVs is elaborated by considering different case studies. Moreover, the amount of GHG mitigation significantly high by using a hybrid energy system.
- It is found that the grid-integrated system gives a better performance in terms of both technical and economical, and also from the result, it is observed that solar PV gives better yields comparing that of wind for the location selected.
- A significant increase in fuel cost is observed from the past few years, and the usage of electric vehicles is also increasing in all parts of the country; it is very much necessary to develop EVCS for ensuring energy security in India.
- In the future development of EVCS is very much essential for the transport sector electrification. The proposed system gives a brief idea about designing and optimizing EVCS for future design engineers and policymakers in the transportation sector.

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