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Article

Techno-feasibility (economic & environmental) analysis of EV charging using HRE sources in the work places

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Abstract: Electric vehicles (EVs) are gaining significant acceptance in the domestic market, primarily due to the continuous rise in fossil fuel prices. Conventional internal combustion (IC) engine vehicles are major contributors to greenhouse gas (GHG) emissions, which adversely impact the atmospheric ecosystem. However, one of the major challenges associated with EV adoption is the limited availability of charging infrastructure. To address this issue, the present research investigates the feasibility of charging EVs using hybrid renewable energy (HRE) sources operating in a grid-connected mode. The study emphasizes the effective utilization of renewable resources for daytime EV charging; a detailed assessment of the renewable energy potential at the study site was carried out, and corresponding power-source models were developed by considering practical and real-time operating constraints. The optimization process focused on key economic indicators, including capital investment, replacement cost, and operation and maintenance (O&M) cost, with the objective of minimizing the cost of energy (COE), reducing the net present cost (NPC) of the HRE system, and lowering GHG emissions. The load-following (LF) algorithm was used to optimize the hybrid configuration, and the performance of the selected system is comprehensively discussed. The optimized HRE model comprising a biomass-based generator in combination with the grid achieved a minimum COE of Rs. 0.462 per kWh for EV charging. Based on the modeled system, it is estimated that approximately 80 EVs can be charged per day, including 40 two-wheelers and 40 four-wheelers. The unmet load of the optimized configuration was calculated as 0.05%.

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1. Introduction

Fossil fuel-based IC engines have high running costs due to high fuel costs and high demand. Maintenance costs for the IC engine-based vehicle are high, so people have started using the electric

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vehicle (EV.); this population of EVs has increased in the market especially in the city, for the past 2 years from 2020 onwards. Charging this EV is becoming the biggest challenge for the user because of less availability of the charging infrastructure. Charging the EV through the DISCOM power supply, which is dominated by fossil fuel, is also contributing to the emission of GHG to a more significant extent and contributes to the increase in power demand.

Solar-based EV charging infrastructure is becoming feasible from an economic point of view as well as from an environmental point of aspects. Having the rooftop PV system in the residential place would give a dual advantage for the customer, power demand of the residential load and EV load can be fulfilled by both PV and grid [1,2]. The best way to reduce the power demand because of charging the EV in public places and residential places is to use renewable sources [3].

By using HRE sources operating in the grid-connected mode and HRE system in standalone mode we can reduce the GHG emission in the atmosphere and the power demand [4]. The cost of charging EVs can be significantly decreased compared to solely relying on grid supply for EV charging [5]. Fig. 1 [6] illustrates the process of electric vehicle (EV) charging using renewable sources like photovoltaic (PV) and wind energy. The power produced at the central station travels through transmission and distribution networks. It is finally fed to the consumer (commercial building), where the EVs are charged through the EV charger installed at the building premises. The EVs are classified based on the mechanical and electrical drive system employed in the vehicle. The PEV (plug-in EV), HEV (Hybrid Electric Vehicle), and BEV (battery-operated EV) in these PEVs are getting popular in the market due to the simplified drive system, which is wholly operated by the electrical system. The EV charging power demand and traffic details need to be predicted for better usage of power in an effective manner. The EV power demand of the vehicles varies from vehicle to vehicle depending on the energy storage capacity, which in turn influences the charging time of the vehicle. The EV power demand was forecasted based on historical data using a big data analytical model. The charging of EVs in the existing power distribution network introduces a new peak demand in the system, disturbs the power network's healthiness, and introduces the voltage swell in the system due to these power distribution network elements getting overloaded. The best way to eliminate the overload issue is to introduce innovative charging technologies for charging EVs so that this new peak demand created by the EV charger can be mitigated [7]. The charging of EVs in the existing power distribution network introduces a power dip in the network, which causes severe issues for the other loads. The interfacing the EVs with the smart Grid can mitigate the power demand in the network. It can be managed by the renewable sources in the smart Grid by having the Vehicle to Grid (V2G) charging methodologies power balance in the facing distribution network can be managed [8]. The new concept of online electric vehicle (OLEV) is developed to eliminate the problems in the conventional charging infrastructure especially the cost and power demand introduced by the EV charger. OLEV has a small capacity of battery and it can be charged without having any physical contact with the power-delivering unit [9].

Electric vehicle usage in the market is trending; subsequently, EV charging infrastructure wasn't increasing due to scarcity of power demand, cost, and place constraints. These constraints can be eliminated by scheduling charging time using machine algorithms / Artificial intelligence. The practical usage of EV chargers can be enhanced using advanced data analytic techniques without additional infrastructure [10]. The energy storage system becomes a vital part of the EV charging station and can be charged through renewable sources and grid supply. The battery prevents the power demand caused by the EV charger when the output from the renewable source is less [11]. The selection of battery capacity plays a major role in enhancing the reliability of the power distribution network consisting of EV charging load [12]. The energy cost for EV charging can be reduced by adequately scheduling the EV load by adopting a proper DSM (Demand Side management) strategy. The Vehicle charger load can be shifted from peak time to nonpeak time in a day, and we can also adapt the time of use tariff or charging the EV [13]. Fast charging is a DC Fast charger used to charge EVs – Four wheelers that are used to deliver high power to the battery in the vehicle; because of this, charging time for the battery will be less, and the cost of Energy for charging the vehicle using hybrid sources consist of PV, Wind, and Grid would greatly influence the cost of the system. Hybrid energy sources optimization uses the optimization algorithm to size the renewable sources concerning the least cost of Energy (COE) and minimum NPC [14]. The HRE system comprises photovoltaic and biomass-based generators utilized for charging electric vehicles.

The discussion focused on various Hybrid renewable energy (HRE) configurations, considering factors such as the energy cost per kWh, net present cost (NPC), and operational expenses. Additionally, it delved into the modeling of renewable sources and the optimization algorithm employed in the Homer Pro tool [15]. The penetration of renewable energy sources, such as solar PV and wind, into the existing power distribution network is intended to meet the energy needs of the educational institution's load. The primary aim of modelling renewable resources and developing a multi-objective function was to optimize the energy cost to a least value. The technical aspects concerning the sizing of each hybrid renewable source were done concerning cost [16]. The rooftop solar plant in the residential apartment is used to charge the EVs. The design of the photovoltaic plant is accomplished using the Solar Pro tool, whereas the sizing of renewable sources is determined by the available rooftop space of the building. Solar Pro supports the importing of CAD files into it. Thereby, technical aspects of the system design are done. The research evaluated the electrical output of the solar plant in relation to varying weather conditions, with the obtained results utilized to assess the feasibility of electric vehicle (EV) charging [17].

Most of the researchers contributed towards design aspects of power electronics-based converters for EV chargers, and different topologies of converters were designed and validated. In the recent past, not much research was explored in charging the EVs in the work place using the available renewable sources in the site. Charging electric vehicles (EVs) using renewable sources at the workplace will decrease reliance on fossil fuels, thereby lowering the energy costs associated with EV charging and reducing greenhouse gas (GHG) emissions. This can be achieved without requiring additional grid infrastructure. EV charging in the workplace with available renewable sources is explored in this research article, and Modeling of the HRE system was optimized using load following dispatch algorithm.

The adoption of electric vehicles (EVs) is rapidly increasing due to rising fossil fuel costs and growing environmental concerns. However, limited EV charging infrastructure poses challenges in managing peak load demand and energy costs. Relying solely on the conventional grid for EV charging can increase greenhouse gas (GHG) emissions and operational expenses. Integrating hybrid renewable energy (HRE) systems, combining solar PV and biomass sources with energy storage, offers a promising solution for cost-effective and sustainable EV charging. Despite the potential, few studies have explored the techno-economic performance of HRE systems for EV and office load charging in real-site scenarios, considering both grid-connected and standalone operation. This study aims to evaluate and optimize HRE systems to minimize the cost of energy (COE), reduce GHG emissions, and maximize renewable penetration. The findings provide insights for deploying HRE-based EV charging systems in developing countries with similar energy challenges, contributing to cleaner transportation and improved energy management.

The main objective of this research is

1. To develop and model a hybrid renewable energy (HRE) system combining PV, biomass, and energy storage to meet the energy requirements of electric vehicles (EVs) and workplace loads.
2. To optimize the capacity of the HRE components, including energy storage, to minimize the levelized cost of energy (COE) while ensuring reliable energy supply.

3. To evaluate the techno-economic and environmental feasibility of the optimized HRE system, considering cost, reliability, and greenhouse gas (GHG) emissions.
4. To assess the maximum renewable penetration achievable for EV and office loads and reduce dependency on fossil-fuel-based grid supply.
5. To analyze system performance under different configurations (with and without energy storage) and conduct sensitivity analysis to identify cost-effective strategies for EV charging.

This paper is organized as follows: Section 2 presents the Methodology; Section 3 deals with the Modeling of power sources; Section 4 describes the Evaluation of Renewable sources; Section 5 presents Technical Specifications and economic constraints; Section 6 describes the Load Following Algorithm; Section 7 covers Techno-Economic Analysis; and Section 8 presents the Results and Discussion.

2. Methodology

The techno-economic feasibility of the hybrid renewable energy (HRE) system, including renewable sources and energy storage, was analyzed using HOMER Pro. The software applies the Load Following (LF) dispatch strategy to determine optimal system sizing while minimizing the cost of energy (COE), net present cost (NPC), and greenhouse gas (GHG) emissions. The optimization outputs include component sizing, COE, NPC, operating cost, total energy generation, and estimated GHG emissions. Four case studies were evaluated by varying key cost parameters such as biomass fuel price, grid purchase rate, and grid export rate. HRE configurations with and without energy storage were compared to assess differences in performance and economic viability. The steps followed in the optimization process are shown in Figure 1.

2.1. EV Charging Load

A two-wheeler requires 3 units of energy for charging, while a four-wheeler needs 21.5 units [18], giving a combined requirement of 24.5 units. The charging power for one two-wheeler is taken as 1.5 kW [19], and six chargers were considered in this study, totaling 9 kW. For four-wheelers, a 15 kW DC fast charger with two output guns was used, allowing two vehicles to charge simultaneously. The charger draws a peak input power of 32 kW and can charge up to 48 four-wheelers per day, with each charge taking about one hour. According to Table 1, charging 40 two-wheelers and 40 four-wheelers daily requires 980 kWh of energy. In this study, the total connected load for EV charging is 41 kW, including 9 kW for two-wheeler chargers and 32 kW for the DC fast charger. Detailed ratings are provided in Table 2. The total energy demand for charging EV of 40 Nos is 980 kWh and total energy demand is 24.5 kWh.

Table 1. Energy demand of the EV.

Electric Vehicle	Energy demand of EV (Kwh)	Total Energy Demand for charging 40 EVs
Two Wheeler	3	120
Four Wheeler	21.5	860

Table 2. Load demand of the EV Charger.

Electric Vehicle	Load Demand in kW (for one charger)	Total Power Demand (kW)
Two Wheeler	1.5	9
Four Wheeler	32	32
Total Power Demand for EV	33.5	41

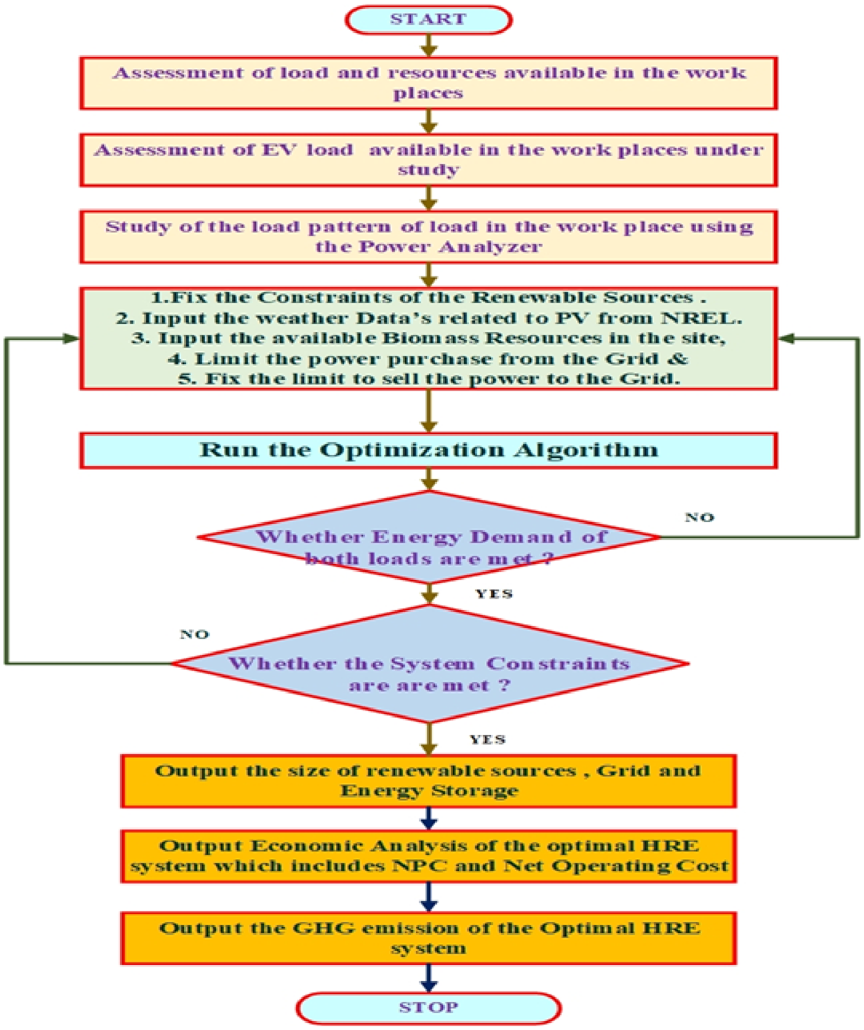

Figure 1. Optimization algorithm steps in Homer Pro.

2.2. Office Load

The supply to the office building under study is fed with LT (Low Tension) from the local DISCOM (Distribution Companies) at 415V, three-phase, 50HZ. The maximum sanctioned demand of the office is 55kW. In this research, two loads were taken for study: load 1 corresponds to EV charging, and Load 2 pertains to the connected load of the workplace consisting of computer, UPS, CNC machinery, Air conditioning, lighting load (office and street light), and fans. The significant load in the office consists of computers, ACs, and CNC machinery. The power demand of the office building load 2 is 246 kWh per day, and the peak load is 41.67 kW. The detailed load pattern of load 2 of the workplace is given in Table 3. Energy Demand of EV load is presented in Figure 2.

Table 3. Power demand of the load in the office.

Name of Module	KWH
Office Rooms	81.721745
Design Lab	39.2533
Mechanical - CNC Lab	92.06
Air COMPRESSOR	3.09
Mechanical - Grinding	1.0081125
Computer Hardware lab	11.866
Electrical Distribution Room	0.7416
Material Storage room	3.7401875
Finance Dept.	12.6896
Lighting load - Building outside	0.24
Average Energy Demand per Day	246

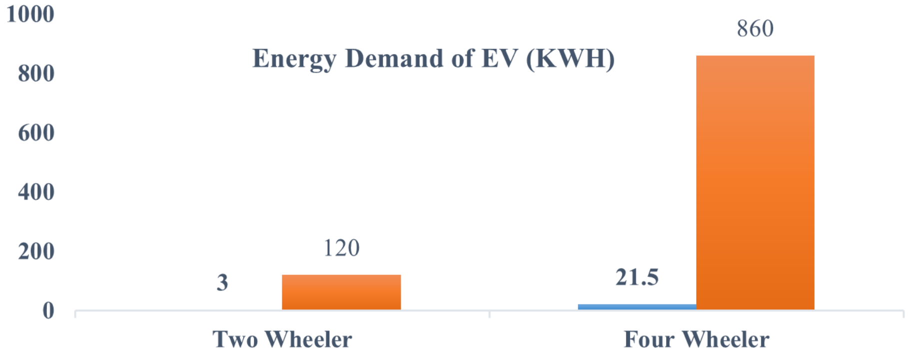

Figure 2. Energy demand of the EV.

The energy demand peaks during the daytime, particularly between 10 a.m. and 1 p.m., when computers and CNC machines operate simultaneously. After 6 p.m., only CNC job work continues, resulting in a lower load compared to daytime. The overall load profile of the system is shown in Figure 3.

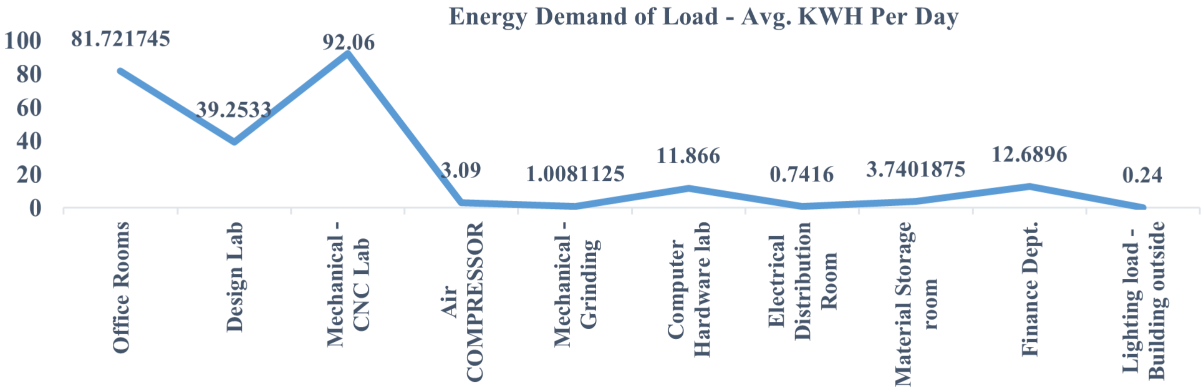

Figure 3. Energy Demand of the Load 2 (Office).

The hourly load profile shows peak demand between 10 a.m. and 1 p.m., with lower demand in the evening. The HRE system, combining PV, biomass, and storage, efficiently meets these fluctuations, storing excess energy during low-load periods and supplying it during peaks to ensure reliable and cost-effective EV and office load operation.

3. Renewable Sources Modelling

In this investigation, two renewable sources, namely solar and biomass, were taken into consideration for the study. The modeling of these renewable resources is elaborated below,

3.1. Solar

The power generation from the PV system depends upon solar Insolation, temperature, derating factors (Manufacturing tolerance, dust, coefficient of power, AC&DC cable loss), Module efficiency, and Inverter efficiency. The electrical output from the solar system [20] is calculated using the Equation 1 given below,

$$PA_{dc} = TE_{pv}.RD_{pv}.\left[\frac{R}{R_{STC}}\right].\left[1 + CT.\left(O_{ct} - O_{ctSTC}\right)\right], \tag{1}$$

where TEpv is the PV array rated Capacity in kW at STC condition (standard test condition), RDpv is the Derating factor of the PV system in percentage (%) which includes all the parameters which influence the output of the PV array, R is the solar Insolation in (kW/m2) available on the PV modules/array at the instant, RSTC is the solar Insolation at STC (1000 W/m2), CT is the coefficient of power pertains to the temperature at the instant of time in [%/°C], Oct is the temperature of the solar cell at the instant of time in [°C], OctSTC is the temperature of the solar cell at STC condition [25°C].

3.2. Bio Mass Based Diesel Generator (BD)

Biomass raw materials available in the site under study are used to generate the biogas, which is used to run the generator [21]. The output from the generator is based on the calorific value of the biogas. The electrical output from the generator is calculated using the Equation 2 given below,

$$\eta_{biodc\ gen} = \left\{\frac{3.6\ BDG_{gen}}{\left[\left(Do + D_1 P_{bgen}\right)\ LHV_{fuel}\right]}\right\}, \tag{2}$$

where ηdcgen is the Biomass-based generator efficiency in percentage (%), Do is the coefficient of fuel curve intercept in [units/hr/kW], D1 is the slope of the fuel curve in [units/hr/kW] and LHVfuel is the Low heating value of the fuel used in the generator.

3.3. Energy Storage Elements

Batteries act as excellent energy storage elements in a microgrid system. The storage element is generally used in a Hybrid renewable power system to increase the system's reliability, which is fed with PV energy and biomass. The fluctuating output from renewable sources can substantially affect the system's reliability. To mitigate this, the output from the energy storage element is utilized to enhance the system's reliability, thereby preventing load outages. Batteries are used as buffer elements to store Energy from renewable sources when there is less load demand and to discharge the Energy when load demand is high, as well as deficit output from renewable sources. The power rating of the battery [20] in the Homer Pro tool at any time can be calculated using the Equation 3 given below,

$$B_P = \frac{K_{batt}.V_{batt}.I_{batt}}{1000}, \tag{3}$$

where, K_{batt} denotes the number of storage elements (battery), V_{batt} represents a rating of the voltage of a single storage element, and E_{batt} denotes the maximum current in amps that can be allowed to charge the battery.

3.4. Converter

A converter was used in this study is used to store the energy in the storage element as well as to supply the AC energy to the loads. The converter considered in this study acts as bidirectional, converting the AC to DC and DC to AC to transfer the Energy between the AC and DC Bus. The converter converts AC to DC and charges the battery, whereas stored Energy in the battery is converted into AC and fed to the load connected to the AC bus. The output of the converter [20] when it operates as an inverter and rectifier is given in the below Equations (4) and (5).

In this study, the Lifespan of the converter is taken as 25 years, and the efficiency of the converter is considered as 90% [22]

$$Po_{inv} = \eta_{inv}.Pdc, \tag{4}$$

$$Po_{rect} = \eta_{rec}.Pac, \tag{5}$$

where Po inv is the output power from the inverter in kW, Po rect is the output power from the rectifier in kw, ηinv is the inverter efficiency in %, ηrec is the efficiency of rectifier in %, Pac is the AC power input in kW, Pdc is the DC power input in kW.

3.5. Grid

Local TSDISCOM supplied the power supply to the office building under the study at 415 voltage, which will act as a grid and is given to the power control center (PCC). The building has sanctioned contract demand of 55kW. The Grid was going to supply the required power to loads connected to the building and the power to the EV charger connected to the electrical power distribution unit (PCC).

Table 4. Grid power parameters for costing.

Power Import capacity in kW	Power Export capacity in kW	Energy purchase price in Rs	Energy selling price in Rs	Demand Rate per kW In Rs
55	5	4	5	10
Reliability				
Mean outage frequency per yr	**Mean repair time(h)**	**Repair time variability (%)**		
15	2	10		

This study's performance of the HRE system will be analyzed with and without an energy storage element. The power exchange between grid and load is fixed based on the DISCOM norms also considered. The value for the same is given in Table 4. The power purchase from grid cost and power export to grid cost are given in Table 4. Based on past historical records of the Grid, performance concerning reliability is noted and considered in this study to check the performance of HRE for proper sizing of renewable sources. The value of power outage per year, mean time to repair the grid failure, and repair time variability in percentage (%) are also considered in this study. During office hours, vehicles are charged mainly using renewable sources.

The emission of greenhouse gas (GHG) from the Grid is also considered in this study to optimize renewable sources sizing concerning cost. The emission of different greenhouse gases from the Grid [20] is given in Table 5.

Table 5. GHG emission from a grid source.

Carbon di oxide (g/kWh)	Sulphur oxides (g/kWh)	Nitrous Oxide (g/kWh)
632	2.74	1.34

4. Evaluation of Renewable Sources

The office building studied is located in Hyderabad, Telangana, India, with abundant year-round solar radiation suitable for PV power generation. Spread over 15 acres with greenery, the site provides biomass resources such as crop residues, plant waste, and food scraps for biogas production. Both PV and biomass availability at the site were considered in modeling the hybrid renewable energy system for this study.

4.1. PV

Latitude and longitude coordinates corresponding to the site under study are 17.387, 78.491. The solar Insolation of the site can be taken from the NREL site [23], and this can imported into our simulation tool for further analysis.

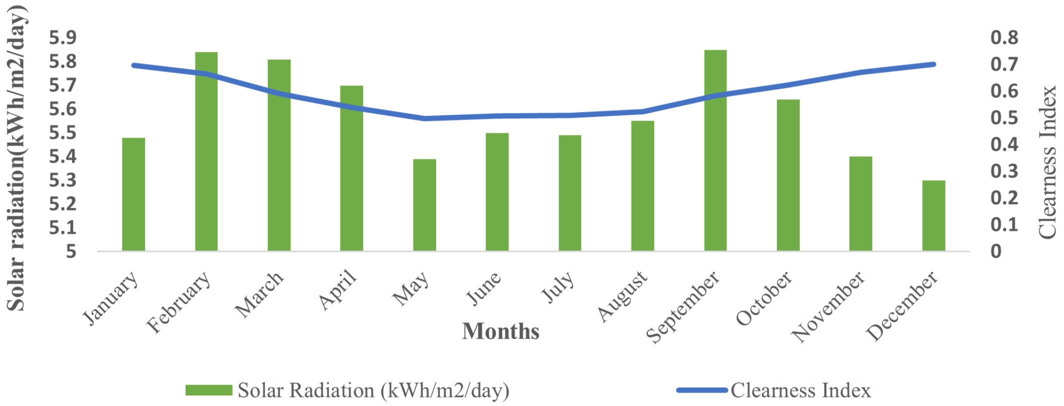

Figure 4. Solar Radiation and clearness index.

The value of the solar Insolation and clearness index available on the site is given in Figure 4. The temperature [23] prevailing in the site is also considered for the study, and the value of the same is shown in Figure 5.

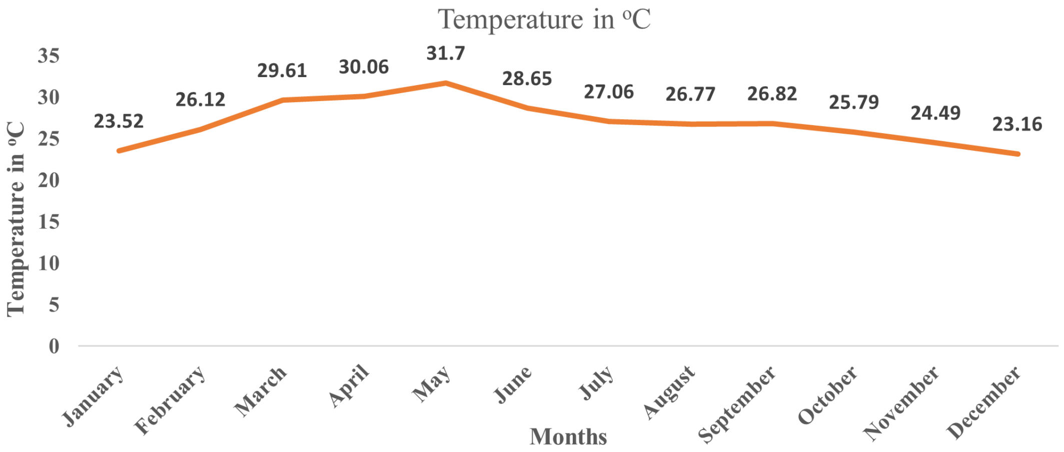

Figure 5. Temperature at the site.

4.2. Biomass

The site has an average daily biomass availability of 10.42 tons from food waste, crops, and plant residues, with lower availability in October (≈5 tons/day) and higher in April and June (≈15 tons/day). The average biomass distribution is shown in Figure 6, and the corresponding biogas production is presented in Table 6.

Table 6. Technical parameters of biogas.

Type of Fuel	Technical Parameters	Value
Biogas	Biomass available (tons/day)	10.42
	Price (USD/tons)	10
	Percentage of Carbon (%)	5
	Density (kg/m^3)	0.72
	Low Heating Value(LHV)of biogas (MJ/kg)	5.5

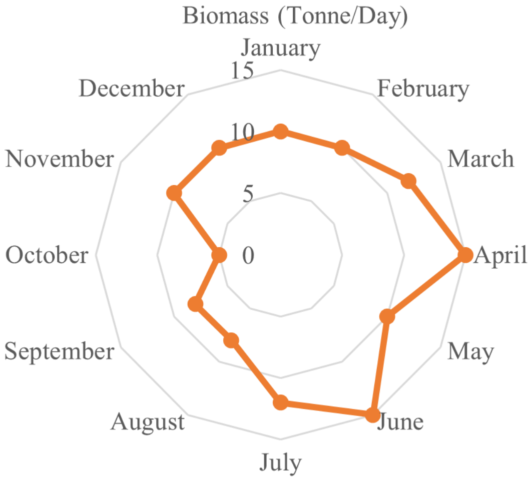

Figure 6. Biomass resources in the site.

4.3. Renewable fraction

The renewable penetration in the system is calculated using the Equation (6) given below,

$$RW_{pen} = \frac{R_o}{P_{load}}, \tag{6}$$

where R_o is the total power output in kW from the renewable sources, P_{load} is the total electrical load connected in the system in kW.

4.4. Emission of GHG

By using renewable Energy, the emission of GHG [24] can be significantly reduced, and the type of gas emission from the power generating unit depends on the fuel used. The emission of carbon dioxide from fossil fuel-based generators is calculated using the relation (7) given below,

$$T_{CO_2} = 3.667.T_f.LHV_f.EF_f.XF_c \tag{7}$$

Where TCO2 is the total emission of CO2, Tf is the total fuel consumed by the biomass generator in a liter, LHVf is the low heating value of the fuel in MJ/L, EFf denotes the carbon emission factor in tonne carbon/Tj, and XFc denotes the oxidized percentage of carbon i.e. 1 gram of carbon present in the 3.667 gram of CO2. The reduction CO2 emission [24] from the Hybrid system is calculated using the relation (8) given below,

$$\%CO_2 \text{ savings} = \frac{\text{Emission}_{\text{DG set}} - \text{Emission}_{\text{Hybrid Renewable system}}}{\text{Emission}_{\text{DG set}}} \times 100 \tag{8}$$

5. Technical Specification, Economics & Constraints of Renewable Sources

The investment, recurring, and operation and maintenance costs of the renewable sources were estimated using current market prices in India.

Table 7. Specification of sources.

Name of the component	Specification	Value
Solar Panel [20,25,26]	Generic flat plate – Monocrystalline	1000W
	Derating Factor	80%
	Nominal Operating Cell Temperature (NOCT)	44°c
Biogas System [27]	Capacity of Gr	50kW
Battery [26,28]	Nominal Capacity of battery	3.11kWh
	Nominal Voltage of Battery	12V
	Maximum Capacity (Ah)	260
	Round Trip Efficiency	80%
	Min. State of charge	20%
Converter [26,28]	Rated Capacity	1kW
	Efficiency of Inverter	95%
	Efficiency of Rectifier	95%

The renewable source specifications used in this study were based on locally available market data. Biomass-based biogas generation was costed at a base rate of Rs 10 per ton. Technical details of the PV, biomass, and battery systems are listed in Table 7, while Table 8 presents their respective cost inputs used for optimization. Each component was evaluated with a 25-year lifetime, considering capital, replacement, operation and maintenance, and fuel costs.

Table 8. Cost details of renewable sources.

Name of Component	**Cost (Rs)**	**Replacement Cost(Rs)**	**Fuel Cost (Rs)/kWh**	**O&M Cost(Rs)**	**Life Time of Component in Years /Hrs**
PV System [26,29]	40000/kW	40000/kW	-	10000/year	25 yrs.
Biogas System [28]	3000/kW	3000/kW	10	0.1/hr	219000 hrs
Battery [26,28]	410/battery	350/battery	-	120/year	25 yrs.
Converter [26,28]	300/kW	300/kW	-	1/year	25 yrs.

In this study, the project assumes an interest rate of 8% and an inflation rate of 2%. The PV system is limited to a maximum capacity of 300 kW, the battery bank is capped at 100 units, and the biogas generator has a maximum capacity of 50 kW.

6. Load Following (LF) Dispatch Algorithm

The Load Following (LF) dispatch strategy is used to optimize the HRE system by minimizing energy cost while prioritizing renewable power. In this approach, energy generated from renewable sources mainly PV is supplied to the load first. Any surplus is used to charge the battery, and only when the battery is full is excess power exported to the grid. Biomass generation is used next to support the load and charge storage when needed. Grid power is given the lowest priority and is imported only when renewable and storage sources cannot meet the demand.

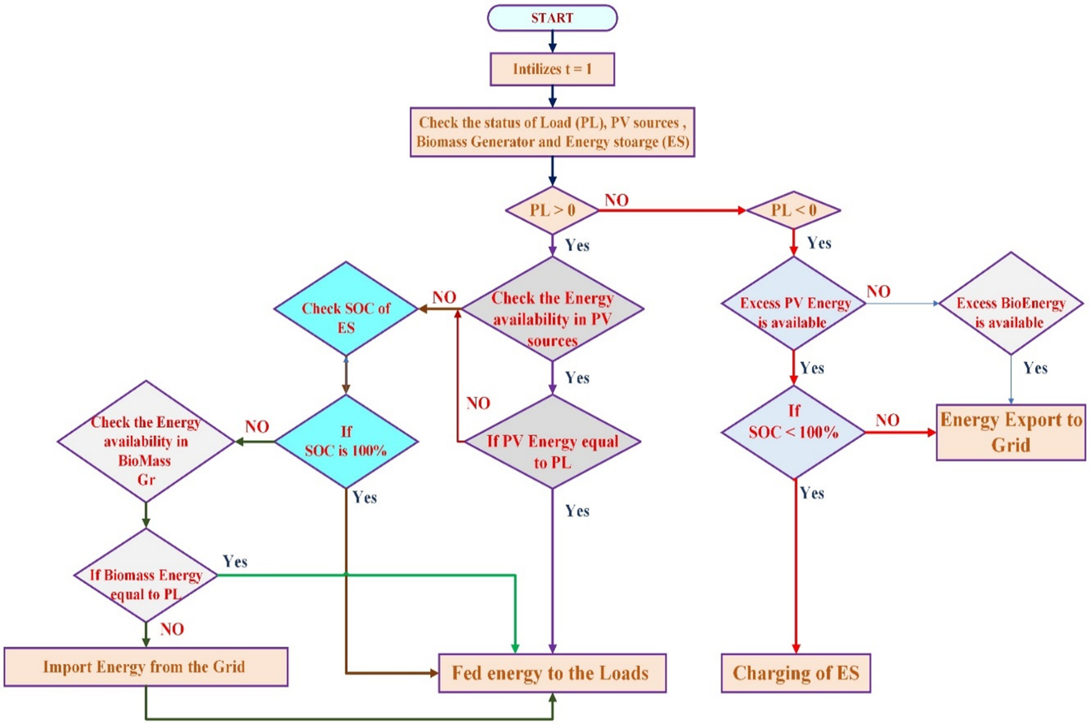

Figure 7. Load Following Dispatch algorithm.

When load demand exceeds renewable generation, the battery discharges to supply the deficit. If the battery cannot meet the required load, the system draws from the grid or operates the biomass generator. Battery charging occurs only from PV or biomass sources, and grid power is never used to charge the storage system. Likewise, energy from the battery is not exported to the grid. The overall LF dispatch process is shown in Figure 7.

7. Techno-Economic Analysis of Grid-Dependent HRE System

Accurate sizing of renewable sources is essential to prevent power deficits in the HRE system and ensure reliable operation [30]. The financial analysis considers capital investment, operation and maintenance costs, replacement costs, net present cost (NPC), and other operational expenses, which together determine the overall cost of energy (COE) from the renewable sources [31].

7.1. Capital Recovery factor (CRF)

CRF [20] is used to access the present value of the annuity of each component of a Hybrid renewable system (HRE). CRF is calculated using the Equation (9) given below,

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}, \tag{9}$$

where i is the real discount rate, and N is the project lifetime in years.

7.2. ACC - Annualized Capital Cost

The ACC is the product of each source's capital recovery factor and capital cost [32]. The ACC is calculated using the Equation (10) given below,

$$ACC = CRF(i,N).\sum_{i=1}^{n} C,i\ (Rs/Year), \tag{10}$$

where C is the capital cost of power sources in rupees, n is no of power sources components, i is the real discount rate, and N is the project lifetime.

7.3. ASC - Annualized System Cost

The Annualized system cost includes the sum of the annualized cost of the capital cost of the equipment plus the replacement cost of the equipment plus the O&M cost of the equipment minus salvage value [32,33]. The ASC is calculated using the Equation (11) given below,

$$ASC = \sum_{i=1}^{n} ACCi + AO\&Mi + ARCi - SAi\ (Rs/Yr) \tag{11}$$

where ACC is the Annualized capital cost, AO&M is the Annualized operation and maintenance cost, ARC is the Annualized replacement cost, SA is the salvage value, and n is the number of power sources.

7.4. COE - Cost of Energy

The cost of Energy indicates the cost per Energy generated (kWh) [34], and it is calculated using the relation given below,

$$COE = \frac{ACS}{\text{ENERGY SERVED}}\ (Rs/kWh) \tag{12}$$

7.5. NPC

The total cost of the system is calculated based on the annualized cost of the system for the capital recovery factor [32], and it is calculated using the relation given below.

$$NPC = \frac{ACS}{CRF(i,N)}.(R) \tag{13}$$

8. Results & Discussion

Modeling of the hybrid renewable system was conducted using the Homer Pro tool and using Load following dispatch algorithm optimization of the Hybrid renewable system was carried out [3]. The performance of a hybrid renewable energy system, both with and without energy storage, is evaluated based on optimization results, focusing on cost factors like the levelized cost of energy (LCOE), net present cost (NPC), and greenhouse gas (GHG) emissions. The results of the optimization of HRE is discussed below,

8.1. Case 1: HRE With Energy Storage

In this system, the energy storage element was considered for the study apart from the renewable sources (PV & Bio mass Gr). The HRE system with battery was modeled in the Homer Pro tool and it is shown in Fig. 8. The optimization result of the system is discussed below, and the result is shown in Annexure A.

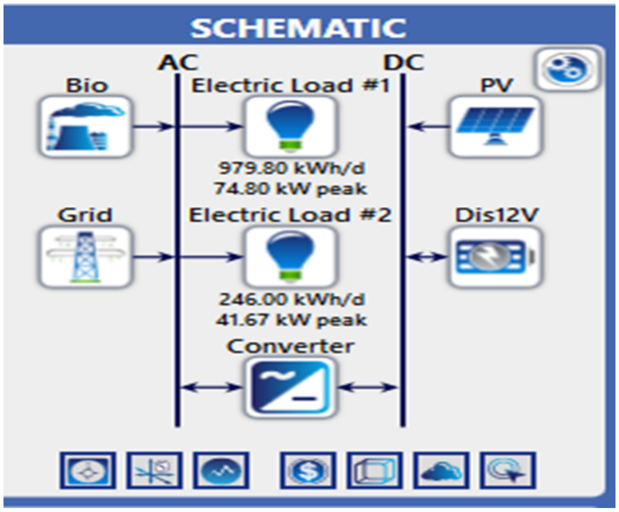

Figure 8. HRE system with energy storage.

8.1.1. BG-Grid

This system's energy cost is Rs 0.426 per kWh, and the Biomass generator is sized to 50 kW. The Renewable fraction in this system is 89.50%, NPC is 2561553, and emission of CO2, SOX & NOX is 31068 kg/yr, 2.50 kg/yr, and 67 kg/yr, respectively. The unmet electrical load is 0.05%.

8.1.2. BG-ES-Grid

The energy cost in this system is Rs 0.428 per kWh, the Biomass generator is sized to 50 kW, and only one battery is selected. The Renewable fraction in this system is 89.50%, NPC is 2570333, and CO2, CO, SOX & NOX emissions are 30904 kg/yr, 2.50 kg/yr, 133 kg/yr, and 67 kg/yr, respectively. The unmet electrical load is less than 1% and it is about 0.05%.

8.1.3. PV-BG-ES-Grid

This system’s energy cost is Rs 0.623 per kWh, and PV, Biomass generator and battery is sized to 100, 50 kW, and 104 batteries are selected. The Renewable fraction in this system is 99.59%, NPC is 3820798, and CO2, CO, SOX & NOX emissions are 1406 kg/yr, 2.2 kg/yr, 5.23 kg/yr and 3.94 kg/yr, respectively. The unmet electrical load is less than 1% and it is about 0.004%.

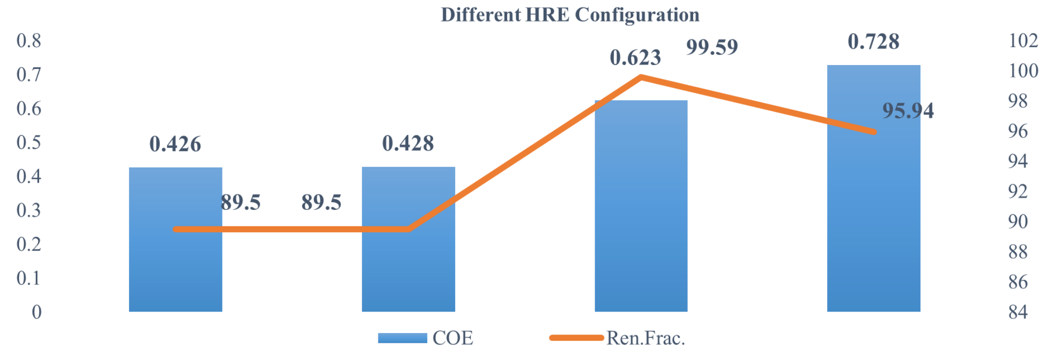

Figure 9. Renewable fraction and COE for different HRE configuration.

Figure 9 depicts the renewable energy fraction and COE for different HRE configurations without energy storage systems.

8.1.4. PV-BG-Grid

This system’s energy cost is Rs 0.728 per kWh, and the PV and Biomass generator is sized to 100 and 50 kW. The Renewable fraction in this system is 95.94%, NPC is 3820798, and emissions of CO2, CO, SOX & NOX is 12391 kg/yr, 1.97 kg/yr, 53 kg/yr, and 27.1 kg/yr, respectively. The unmet electrical load is less than 1% and it is about 0.011%.

8.2. Case 2: HRE Without Energy Storage

Renewable sources (PV & Bio mass Gr) and grid elements were considered for the study in this system. The HRE system with Grid was modeled in the Homer Pro tool, and it is shown in Fig. 10. The optimization result of the system is given below, and the result is shown in Annexure B.

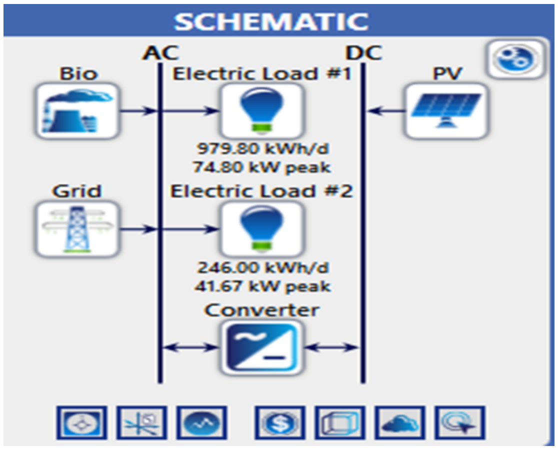

Figure 10. HRE without storage.

8.2.1. BG- Grid

This system's levelized energy cost is Rs 0.426 per kWh, and the Biomass generator is sized to 50 kW. The Renewable fraction in this system is 89.50%, NPC is 2561553, and emission of CO2, CO, SOX & NOX is 31068 kg//yr, 2.50 kg/yr, 134 Kg/yr, and 67 kg/yr, respectively. The unmet electrical load is less than 1% and it is about 0.05%.

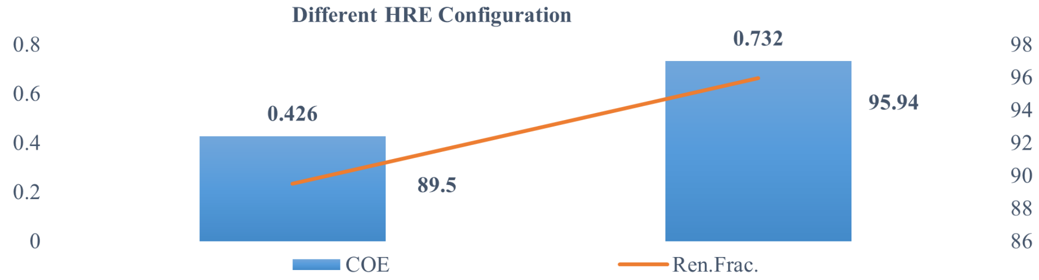

Figure 11. Renewable Fraction and COE for Different HRE Configuration.

Fig. 11 depicts the renewable energy fraction and COE for different HRE configurations without an energy storage system.

8.2.2. PV-BG-Grid

This system's energy cost is Rs 0.732 per kWh, and the PV and Biomass generator is sized to 100 and 50 kW. The Renewable fraction in this system is 95.94%, NPC is 4512313, and emission of CO2, CO, SOX & NOX is 12402 kg//yr, 2.03 kg/yr, 53 kg/yr, and 27.2 kg/yr, respectively. The unmet electrical load is less than 1% and it is about 0.011%.

8.3. Case 3: Sensitivity Analysis: HRE With Energy Storage

The Sensitivity Analysis modified the cost of Biogas fuel, power export, import charges, and project lifetime. The sensitivity analysis of the HRE system was studied with and without an energy storage system. The result of the Hybrid Power system (HRE) system is discussed below.

The parameters considered for the sensitivity analysis of HRE with energy storage is given in Table 9. The result of the HRE with energy storage is shown in Annexure C.

Table 9. Sensitivity Parameters.

S.No	Parameters	Value
1	Bio fuel cost per ton	Rs 20
2	Grid Purchase cost	Rs 5
3	Grid selling cost	Rs 6
4	Demand Rate per kW	Rs 15
5	Grid Sale capacity	5 kW
6	Grid Purchase capacity	155 kW
7	Project Life Time	15 years

8.3.1. PV-BG –ES –GRID

The levelized cost of Energy in this system is Rs 1.05 per kWh. The PV, battery, and Bio mass generator size is optimized to 100kW, 205 no's of batteries, and 50kW, respectively. The Renewable fraction in this system is 96.241%, NPC is 5070751, and emission of CO2, CO, SOX & NOX is 13406 kg//yr, 2.42 kg/yr, 57.2 Kg/yr and 29.5 kg/yr, respectively. The unmet electrical load is less than 1%, and it is about 0.02%.

8.3.2. PV-BG-GRID

The levelized cost of Energy in this system is Rs 1.50 per kWh. The PV and Bio mass generator size is optimized to 131kW, and 50kW respectively. The Renewable fraction in this system is 90.19%, NPC is 7257266, and emissions of CO2, CO, SOX & NOX is 34807 kg//yr, 2.03 kg/yr, 150 Kg/yr and 74.7 kg/yr, respectively. The unmet electrical load is less than 1%, and it is about 0.02%.

8.4. Case 4: Sensitivity Analysis: HRE Without Energy Storage

The performance of the HRE system without energy storage is discussed below. The result of the HRE with energy storage is shown in Annexure D.

8.4.1. BG-GRID

The levelized cost of Energy in this system is Rs 1.44 per kWh. The size of the Biomass generator is optimized to 50kW. The Renewable fraction in this system is 72.13%, NPC is 6887384, and emission of CO2, CO, SOX & NOX is 97708 kg//yr, 2.41 kg/yr, 423 Kg/yr and 208 kg/yr, respectively. The unmet electrical load is less than 1%, and it is about 0.05%.

8.4.2. PV-BG-GRID

The levelized cost of Energy in this system is Rs 1.56 per kWh. The PV and Bio mass generator size is optimized to 150kW and 50kW. The Renewable fraction in this system is 91.49%, NPC is 7585208, and emission of CO2, CO, SOX & NOX is 30405 kg//yr, 2.02 kg/yr, 131 Kg/yr, and 65.3 kg/yr, respectively. The unmet electrical load is less than 1%, and it is about 0.01%.

The results indicate that HRE configurations with energy storage outperform systems without storage in terms of renewable penetration, reliability, and cost of energy. Load-following optimization ensures that daytime renewable generation meets EV and office demand, while storage buffers fluctuations, reducing dependence on the grid. Economic analysis shows that hybrid systems can lower the COE and net present cost (NPC), although sensitivity to biomass cost, grid electricity price, and storage capacity affects overall performance. Environmentally, the integration of PV and biomass significantly reduces GHG emissions compared to grid-only charging. These findings demonstrate that HRE systems can meet the energy requirements of EVs and office loads without additional grid infrastructure, highlighting their applicability in other developing countries with similar renewable resources and energy constraints. Limitations of this study include reliance on site-specific renewable availability and daytime charging, suggesting that future work could explore full 24-hour operation, larger EV fleets, and alternative renewable combinations.

9. Limitations, Policy Implications, and Applicability

9.1. Limitations:

This study is limited by the dependence on site-specific renewable resources, particularly solar availability and biomass supply, which may fluctuate seasonally. The economic analysis is based on estimated cost values that could vary in real conditions. The load-following algorithm used for optimization also does not fully account for unexpected grid disturbances or long-term variations in EV charging patterns. Additionally, the focus is mainly on daytime charging, so round-the-clock performance was not assessed.

9.2. Policy Implications:

The results indicate the need for stronger policy support to promote renewable-based EV charging. Incentives such as reduced-interest loans, subsidies, and clear rules for connecting hybrid systems to the grid would enable wider adoption. Policies that encourage biomass management and decentralized power generation can also improve system affordability and reliability.

9.3. Applicability:

The proposed approach can be adapted to other developing countries with similar challenge limited charging infrastructure, high fuel costs, and strong renewable potential. The framework provides a scalable method for planning cost-effective and low-emission EV charging systems.

10. Conclusion

The results of the study show that hybrid renewable energy (HRE) systems provide an economically viable and environmentally sustainable option for workplace EV charging. The analysis includes a detailed evaluation of a base case and a sensitivity case, examining four different system configurations optimized through a dispatch algorithm. In the base scenario, biomass fuel is priced at Rs. 10 per ton, grid purchase at Rs. 4 per kWh, and grid export at Rs. 5 per kWh. For the sensitivity scenario, biomass cost is increased to Rs. 20 per ton, grid purchase to Rs. 5 per kWh, and grid export to Rs. 6 per kWh. Case 1 includes an HRE system equipped with energy storage, combining a biomass generator, storage unit, and the grid. This configuration achieves the lowest cost of energy while supplying both EV charging and office loads. Case 2 excludes the storage component and relies only on a biomass generator and the grid. In both cases, the unmet load remains below 1%, confirming that the EV charging demand and office energy requirements are fully satisfied. The sensitivity analysis shows that increasing biomass fuel cost leads to a rise in the overall cost of energy. The configuration with storage delivers higher renewable penetration and a lower COE compared to the system without storage. Overall, integrating HRE systems for EV charging increases renewable energy share, reduces greenhouse gas emissions, and lowers charging costs. The findings indicate that hybrid systems can reliably meet the full energy demand for EVs and workplace loads without requiring additional grid upgrades.

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Author contributions: First Author made a detailed literature survey pertaining to this research work and contributed in physical surveying of complete HRE system i.e Section 4, 5 and 6. Second Author mentored the first author in writing the research article and he contributed in reviewing and editing the paper. He contributed in interpreting the results took from the hardware setup and given his input in writing the conclusion.

Disclosure statement: All the information collected and presented in this research paper is correct and no influence has been done in getting the data from the third party and all the data presented in this paper is duly collected and measured by the authors. Authors had no conflict of interest in submitting this research paper to the journal.

References

[1] George Fernandez Savari, M. Jagabar Sathik, L. Anantha Raman, Adel El-Shahat, Hany M. Hasanien, Dhafer Almakhles, Shady H. E. Abdel Aleem, and Ahmed I. Omar. Assessment of charging technologies, infrastructure and charging station recommendation schemes of electric vehicles: a review. *Ain Shams Engineering Journal*, 13(6):101938, 2022.

[2] Larry Dickerman and Jessica Harrison. A new car, a new grid. *IEEE Power and Energy Magazine*, 8(2):55–61, 2010.

[3] Li He and Zhixin Wu. Advancing sustainable EV charging infrastructure: A hybrid solar-wind fast charging station with demand response. *Renewable Energy*, 237:121843, 2024.

[4] Anis ur Rehman, Haris M. Khalid, and S. M. Muyeen. Grid-integrated solutions for sustainable EV charging: a comparative study of renewable energy and battery storage systems. *Frontiers in Energy Research*, 12:1403883, 2024.

[5] Mohd Bilal, Fareed Ahmad, and M. Rizwan. Techno-economic assessment of grid and renewable powered electric vehicle charging stations in India using a modified metaheuristic technique. *Energy Conversion and Management*, 284:116995, 2023.

[6] George Fernandez Savari, M. Jagabar Sathik, L. Anantha Raman, Adel El-Shahat, Hany M. Hasanien, Dhafer Almakhles, Shady H. E. Abdel Aleem, and Ahmed I. Omar. Assessment of charging technologies, infrastructure and charging station recommendation schemes of electric vehicles: A review. *Ain Shams Engineering Journal*, 14(4):101938, 2023.

[7] Kejun Qian, Chengke Zhou, M. Allan, and Yue Yuan. Load model for prediction of electric vehicle charging demand. In *2010 International Conference on Power System Technology (POWERCON)*, pages 1–6, Zhejiang, China, 2010.

[8] Jia Ying Yong, Vigna K. Ramachandaramurthy, Kang Miao Tan, and N. Mithulananthan. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renewable and Sustainable Energy Reviews*, 49:365–385, 2015.

[9] Nam Pyo Suh, Dong-Ho Cho, and Chun T. Rim. Design of online electric vehicle (OLEV). In *Global Product Development: Proceedings of the 20th CIRP Design Conference, Ecole Centrale de Nantes, Nantes, France*, pages 3–8. Springer Berlin Heidelberg, 2011.

[10] S. Shahriar, A. R. Al-Ali, A. H. Osman, S. Dhou, and M. Nijim. Machine learning approaches for EV charging behavior: A review. *IEEE Access*, 8:168980–168993, 2020.

[11] Stefania Mitova and Rudy Kahsar. Urban energy system impact analysis: integration of household solar panels and electric vehicles into smart cities via storage and smart charging. *Renewable Energy and Environmental Sustainability*, 7:25, 2022.

[12] M. C. Falvo, D. Sbordone, I. S. Bayram, and M. Devetsikiotis. EV charging stations and modes: International standards. In *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pages 1134–1139, Ischia, Italy, 2014.

[13] Yijia Cao, Shaowu Tang, Canbing Li, Peng Zhang, Yi Tan, Zhenyu Zhang, and Junxiong Li. An optimized EV charging model considering TOU price and SOC curve. *IEEE Transactions on Smart Grid*, 3(1):388–393, 2012.

[14] J. A. Domínguez-Navarro, R. Dufo-López, J. M. Yusta-Loyo, J. S. Artal-Sevil, and J. L. Bernal-Agüstín. Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems. *International Journal of Electrical Power & Energy Systems*, 105:46–58, 2019.

[15] T. Muthukumaran, P. Ajay D. Vimal Raj, and K. Murugaperumal. Feasibility analysis of electric vehicle charging in working places using hybrid renewable sources. In *2022 IEEE 2nd International Conference on Sustainable Energy and Future Electric Transportation (SeFeT)*. IEEE, 2022.

[16] Muthukumaran T., Ajay D. Vimal Raj. P, Murugaperumal K., and Subramaniam NP. Feasibility analysis of PV/Wind/DG based hybrid energy system design for indian educational institute. In *2021 Innovations in Power and Advanced Computing Technologies (i-PACT)*, pages 1–6, Kuala Lumpur, Malaysia, 2021.

[17] T. Muthukumaran, P. Ajay-D-Vimal Raj, K. Murugaperumal, and N. P. Subramaniam. Designing of solar PV plant for EV charging application in residential apartment using solar pro software. *The Institution of Engineers (India) Annual Technical Volume (ATV)*, pages 17–23, 2021.

[18] e-AMRIT, NITI Aayog. Standards and specifications for EV charging. https://e-amrit.niti.gov.in/standards-and-specifications, 2023. Accessed: Mar. 21, 2023.

[19] Plug-in India. Bharat EV specifications for AC and DC charging — everything you need to know. https://www.pluginindia.com/blogs/bharat-ev-specifications-for-ac-and-dc-charging-everything-you-need-to-know, 2023. Accessed: Apr. 5, 2023.

[20] HOMER Energy. HOMER Pro software. https://www.homerenergy.com, 2022. Accessed: Aug. 11, 2022.

[21] Mohammad Reza Akhtari and Mehdi Baneshi. Techno-economic assessment and optimization of a hybrid renewable co-supply of electricity, heat and hydrogen system to enhance performance by recovering excess electricity for a large energy consumer. *Energy Conversion and Management*, 188:131–141, 2019.

[22] Sunanda Sinha and S. S. Chandel. Analysis of fixed tilt and sun tracking photovoltaic–micro wind based hybrid power systems. *Energy Conversion and Management*, 115:265–275, 2016.

[23] National Renewable Energy Laboratory (NREL). NSRDB data viewer. https://nsrdb.nrel.gov/data-viewer, 2022. Accessed: Jun. 14, 2022.

[24] M. R. Elkadeem, Shaorong Wang, Ahmed M. Azmy, Eman G. Atiya, Zia Ullah, and Swellam W. Sharshir. A systematic decision-making approach for planning and assessment of hybrid renewable energy-based microgrid with techno-economic optimization: A case study on an urban community in Egypt. *Sustainable Cities and Society*, 54:102013, 2020.

[25] Fabrizio Fattori, Norma Anglani, and Giovanni Muliere. Combining photovoltaic energy with electric vehicles, smart charging and vehicle-to-grid. *Solar Energy*, 110:438–451, 2014.

[26] L. Olatomiwa, S. Mekhilef, A. S. N. Huda, and K. Sanusi. Techno-economic analysis of hybrid PV-diesel-battery and PV-wind-diesel-battery power systems for mobile BTS: the way forward for rural development. *Energy Science & Engineering*, 3(4):271–285, 2015.

[27] IndiaMART. IndiaMART – B2B marketplace. https://indiamart.com, 2019. Accessed: Oct. 15–20, 2019.

[28] Vikram Solar. DS-5BB-72-Eld-Grand-1000V datasheet. https://www.vikramsolar.com/wp-content/uploads/2015/12/DS-5BB-72-Eld-Grand-1000V-Dec18.pdf, 2015. Accessed: Oct. 8, 2019.

[29] Solar Experts India. Solar panels price list – vikram solar. https://solarexpertsindia.com/solar-panels-price-100w-150w-160w-250w-260w-270w-325w-335w/vikram-solar, 2019. Accessed: Oct. 8, 2019.

[30] Akash Kumar, A. R. Singh, Yanli Deng, Xiangning He, Praveen Kumar, and R. C. Bansal. A novel methodological framework for the design of sustainable rural microgrid for developing nations. *IEEE Access*, 6:24925–24951, 2018.

[31] K. Murugaperumal and P. Ajay-D-Vimal Raj. Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification. *Solar Energy*, 188:1068–1083, 2019.

[32] T. Adefarati and R. C. Bansal. Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources. *Applied Energy*, 206:911–933, 2017.

[33] Anurag Chauhan and R. P. Saini. A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, 38:99–120, 2014.

[34] Md Mustafizur Rahman, Ayokunle Oluwaseun Oni, Eskinder Gemechu, and Amit Kumar. The development of a techno-economic model for assessment of cost of energy storage for vehicle-to-grid applications in a cold climate. *Energy*, 262:125398, 2023.

Appendix – I

a) Previous studies have shown that EV charging performance is strongly influenced by site-specific factors, such as local solar radiation and biomass availability. While some research has explored PV- or biomass-based charging, few studies have investigated hybrid renewable energy (HRE) systems combining multiple sources with storage to optimize cost, reliability, and emissions. The effects of different system configurations, including grid-connected and standalone modes, on EV charging efficiency have also been underexplored. Furthermore, comprehensive techno-economic and environmental analyses for HRE-based EV charging at real sites are limited. This highlights a clear research gap in understanding how hybrid renewable systems can be tailored to site-specific conditions, enabling cost-effective, reliable, and sustainable EV charging infrastructure.

Site-Specific Renewable Availability: Previous studies indicate that EV charging performance and renewable energy integration are highly dependent on local solar irradiation and biomass resource availability. Few studies have systematically assessed this variability for different site locations.

Hybrid Renewable Energy Systems: While some studies have explored PV or biomass-based EV charging, limited research has examined hybrid systems combining multiple renewable sources with energy storage to optimize cost and reliability at real sites.

Grid-Connected vs. Standalone Operation: The impact of system configuration (grid-connected versus standalone) on EV charging efficiency, GHG reduction, and energy cost has not been extensively analyzed across different site scenarios.

Economic and Environmental Assessment: Existing literature often lacks a comprehensive techno-economic and environmental assessment (COE, NPC, and emissions) for hybrid renewable systems applied to EV charging at specific locations.

Scalability and Policy Relevance: Few studies have considered the practical implications for deploying hybrid EV charging infrastructure in developing countries with site-specific constraints. These points now clearly define the research gap and justify the motivation for our study, emphasizing the novelty and site-specific contribution of the work.

b) **Short paragraph discussing the hourly load performance**

The hourly load profile of the system highlights variations in energy demand throughout the day for both EV charging and workplace consumption. Peak demand occurs between 10 a.m. and 1 p.m., when computers, air conditioners, and CNC machines operate simultaneously, while demand drops in the evening when only limited CNC job work continues. This analysis demonstrates how the hybrid renewable energy (HRE) system, including PV, biomass, and energy storage, meets fluctuating loads efficiently. Energy storage plays a key role in balancing supply and demand, storing excess renewable generation during low-load hours and discharging during peak periods, ensuring reliable and cost-effective energy supply to both EV chargers and office loads.

c) Comparison of present research work finding with existing research finding

Name of Research article / Magazine	**Hybrid System Configuration**	**COE (Cost of Energy)**	**NPC (Net Present Cost)**	**GHG Emission Reduction**	**Key Observations**
Present Study/ Work	PV + Biomass + Storage	Rs0.462/kWh	Rs 27,919	Significant reduction	Site-specific optimization; high renewable penetration; reliable EV and office load supply
A hybrid approach based economic assessment EV charging station powered by integrating solar PV and biomass (2024)	PV + Biomass	\$0.80/kWh	N/A	5 kg/h	Hybrid system lowers COE and emissions compared to grid-only
Grid-integrated solutions for sustainable EV charging: a comparative study of renewable energy and battery storage systems (2024)	PV + Battery, grid-connected	\$0.55/kWh	Reduced vs grid-only	Reduced	Renewable integration reduces NPC and COE significantly
Hybrid PV-biogas microgrids for EV charging (2023)	PV + Biogas	\$0.518/kWh	N/A	Substantial	Hybrid PV-biogas reduces energy cost and CO_2 emissions compared to PV-grid or biogas-grid
Techno-economic evaluation of electric vehicle charging stations based on hybrid renewable energy in China (2022)	PV + Wind + Battery	\$0.60/kWh	N/A	N/A	Hybrid systems achieve lower COE than single-source systems across multiple sites

d) Future work

Future work can incorporate real-time monitoring data, more detailed weather forecasting models, and broader sensitivity analysis to improve accuracy. Expanding the evaluation to multiple locations and diverse load categories would provide stronger validation. Integration of advanced control strategies, energy storage optimization, and demand-side management approaches can further enhance system performance. Long-term field testing and techno-economic assessments under varying operational scenarios would also strengthen the practical applicability of the proposed system.

Appendix A

Configuration	Architecture/ PV (kW)	Architecture/ Bio (kW)	Architecture/ Dis12V	Architecture/ Grid (kW)	Architecture/ Converter (kW)	Architecture/ Dispatch	Cost/ COE
BG - Grid	-	50	-	55	-	LF	0.4262
BG - ES - Grid	-	50	1	55	0.147	LF	0.4280
PV-BG-ES-Grid	100	50	104	55	28.845	LF	0.623
PV-BG-Grid	100	50	-	55	68.270	LF	0.728

Configuration	Cost/ NPC	Cost/ Operating cost	Cost/ Initial capital	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	Bio/ Hours
BG - Grid	2561553	186544.2	150000	89.50	1251.57	8760
BG - ES - Grid	2570333	187188.3	150454.1	89.54	1251.60	8760
PV-BG-ES-Grid	3820798	47921.38	3201294	99.59	1109.70	8656
PV-BG-Grid	4492129	102235.2	3170481	95.94	987.41	7798

Configuration	Bio/ Production (kWh)	Bio/ Fuel (kg)	Bio/ O&M Cost	Bio/ Fuel Cost	PV/ Capital Cost	PV/ Production (kWh/yr)	Dis12V/ Autonomy (hr)
BG - Grid	416149	1251.57	43800	125157	-	-	-
BG - ES - Grid	416161	1251.606	43800	125160.06	-	-	0.0487827
PV-BG-ES-Grid	366757	1109.707	43280	110970.07	3000000	172120	5.0734
PV-BG-Grid	326099	987.412	38990	9874.12	3000000	172120	-

Configuration	Dis12V/ Annual Throughput (kWh/yr)	Dis12V/ Nominal Capacity (kWh)	Dis12V/ Usable Nominal Capacity (kWh)	Converter/ Rectifier Mean Output (kW)	Converter/ Inverter Mean Output (kW)	Grid/ Energy Purchased (kWh)	Grid/ Energy Sold (kWh)
BG - Grid	-	-	-	-	-	48800.87	17679.87
BG - ES - Grid	438.7014	3.11447	2.491576	0.05569	0.0425533	48542.41	17297.3
PV-BG-ES-Grid	39321.45	323.9048	259.1239	0.7958202	12.87042	1908.535	26674.27
PV-BG-Grid	-	-	-	0	15.00282	19325.05	29404.49

Appendix B

HRE Configuration	Architecture/ PV (kW)	Architecture/ Bio (kW)	Architecture/ Grid (kW)	Architecture/ Converter (kW)	Architecture/ Dispatch	Cost/ COE
BG-Grid	-	50	55	-	LF	0.426265
PV-BG-Grid	100	50	55	55.32292	LF	0.73211

HRE Configuration	Cost/ NPC	Cost/ Operating cost	Cost/ Initial capital	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	Bio/ Hours
BG-Grid	2561553	1.87E+05	150000	89.50	1251.57	8760
PV-BG-Grid	4512313	1.04E+05	3166597	95.94	1013.26	8100

HRE Configuration	Bio/ Production (kWh)	Bio/ Fuel (kg)	Bio/ O&M Cost	Bio/ Fuel Cost	PV/ Capital Cost	PV/ Production (kWh/yr)
BG-Grid	416149.4	1251.57	43800	12515.7	-	-
PV-BG-Grid	334392.6	1013.265	40500	10132.64	3000000	172120.7

HRE Configuration	Converter/ Rectifier Mean Output (kW)	Converter/ Inverter Mean Output (kW)	Grid/ Energy Purchased (kWh)	Grid/ Energy Sold (kWh)
BG-Grid	-	-	48800.87	17679.87
PV-BG-Grid	0	14.05458	19334.97	29401.16

Appendix C

HRE Configuration	Architecture/ PV (kW)	Architecture/ Bio (kW)	Architecture/ Dis12V	Architecture/ Grid (kW)	Architecture/ Converter (kW)	Architecture/ Dispatch	Cost/ COE
PV-BG-ES-Grid	100.0296	50	205	155	27.96585	LF	1.056992
PV-BG-Grid	131.3824	50	-	155	97.34435	LF	1.503545

HRE Configuration	Cost/ NPC	Cost/ Operating cost	Cost/ Initial capital	System/ Ren Frac (%)	System/ Total Fuel (L/yr)	Bio/ Hours	Bio/ Production (kWh)
PV-BG-ES-Grid	5070751	211456	3243328	96.24	1209.74	8733	401579
PV-BG-Grid	7257266	362944	4120676	90.19	1016.02	7631	336529

HRE Configuration	Bio/ Fuel (kg)	Bio/ O&M Cost	Bio/ Fuel Cost	PV/ Capital Cost	PV/ Production (kWh/yr)	Dis12V/ Autonomy (hr)	Dis12V/ Annual Throughput (kWh/yr)
PV-BG-ES-Grid	1209.7	43665	24195	3000888	161410	8.33	69220.8
PV-BG-Grid	1016.0	38155	20320	3941473	212002	-	-

HRE Configuration	Dis12V/ Nominal Capacity (kWh)	Dis12V/ Usable Nominal Capacity (kWh)	Converter/ Rectifier Mean Output (kW)	Converter/ Inverter Mean Output (kW)	Grid/ Energy Purchased (kWh)	Grid/ Energy Sold (kWh)
PV-BG-ES-Grid	638.46	510.77	0.386	15.55	20866	18334
PV-BG-Grid	-	-	0	19.09	54784	21774

Appendix D

HRE Configuration	Architecture/ PV (kW)	Architecture/ Bio (kW)	Architecture/ Grid (kW)	Architecture/ Converter (kW)	Architecture/ Dispatch	Cost/ COE
BG-Grid	-	50	155	-	LF	1.43
PV-BG-Grid	150	50	155	117.4052	LF	1.56

HRE Configuration	Cost/ NPC	Cost/ Operating cost	Cost/ Initial capital	System/ Ren Frac (%)	System/ Total Fuel (L/yr)
BG-Grid	6887384	7.80E+05	150000	72.12	1206
PV-BG-Grid	7585208	3.36E+05	4685222	91.49	1009

HRE Configuration	Bio/ Hours	Bio/ Production (kWh)	Bio/ Fuel (kg)	Bio/ O&M Cost	Bio/ Fuel Cost	PV/ Capital Cost	PV/ Production (kWh/yr)
BG-Grid	8760	400238.1	1206.109	43800	24122.18	-	-
PV-BG-Grid	7581	334546.2	1009.996	37905	20199.92	4500000	242044.7

HRE Configuration	Converter/ Rectifier Mean Output (kW)	Converter/ Inverter Mean Output (kW)	Grid/ Energy Purchased (kWh)	Grid/ Energy Sold (kWh)
BG-Grid	-	-	154256	16930
PV-BG-Grid	0	20.55503	47821	25396