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Assessment of Microgrid-Integrated Hybrid Electric Vehicle Charging Infrastructure: A Techno-Economic and Environmental Perspective

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Abstract. One of the most important steps in creating a sustainable society is electrifying the transportation industry. There will be a number of benefits, including lower oil use, lower emissions, and grid integration of renewable energy sources. To promote widespread EV adoption, electric vehicle charging station (EVCS) deployment is crucial because it will mitigate "range anxiety," or the worry about how far an EV can go before its battery runs out. In order to reduce costs and emissions, this work will build an electric vehicle charging station that incorporates renewable distributed generation (DG). Standalone microgrid EVCS is examined in various scenarios where energy sources including solar power, wind, and diesel generators are taken into account to meet the EVCS's needs. The model was developed using HOMER software with accurate input data representing its operational, economic, and physical characteristics. This study aims to design an optimal hybrid EVCS integrating renewable energy sources. The system is implemented using HOMER software and evaluated using techno-economic parameters such as net present cost (NPC) and cost of energy (COE). The paper is organized as follows: Section 2 presents the site description, Section 3 explains the system configuration, Section 4 discusses results, and Section 5 concludes the study.

1 Introduction

Globalisation has caused people to live far from their places of employment, travel more, and buy products from around the globe. Due to increased use of transport, 31.7% of the world's oil consumption in 2023 was attributed to this sector, resulting in 35 billion tonnes of CO2 emissions annually [1]. Reduced reliance on oil, lower energy use, and a smaller environmental impact of the transportation system are all priorities. Electricity is a viable way to solve the problems associated with the transportation sector [2]. Since electric vehicles provide several advantages, they are a promising way to guarantee a sustainable transportation system. Economically speaking, electric vehicles (EVs) are more costly to purchase than internal combustion engine vehicles (ICEVs). Nevertheless, compared to ICEVs, the electric motor used in EVs operates with significantly higher efficiency than the internal combustion engine, lowering operating costs. The electric motor's great efficiency will lower overall CO2 emissions from an environmental perspective, even in an electrical system that generates a significant portion of its power from fossil fuels. Incorporating renewable energy sources into the current electrical system might also be a significant consideration from the perspective of the electric grid [3].

Coordinated charging refers to the controlled scheduling of charging activities of plug-in electric vehicles (PEVs), whereas uncoordinated charging refers to uncontrolled and random charging without scheduling. Coordinate charging, an EV charge management method, network reinforcements, and embedded generation are necessary for the safe integration of plug-in electric vehicles (PEVs) into the grid. Coordinate charging is not as robust as it may be due to a lack of precise PEV charging data. When PEV penetration rises to a high level in the upcoming years, this could get even better. Uncoordinated PEV charging must be allowed until then. It will be expensive and time-consuming to upgrade the infrastructure to handle the disorganised PEVs. Furthermore, if conventional power generation is used to supply the uncoordinated PEVs, the emissions from the transportation sector will be transferred to the generation sector. In order to handle the increase in uncoordinated PEV loads, it is crucial to take into account renewable DG [4]. The integration of PEVs and renewable energy resources (RES) has been the subject of numerous contributions in the literature. According to a survey done in [5], EV users would use EVCS stations 433% more frequently if renewable energy was available. Through simulation, the advantages of EVCS's use of renewable generation were validated in [6-8].

A solar-powered EVCS with V2G that is connected to the grid was developed and tested in [9]. According to this study, on gloomy days, the EVCS can balance the load demand in the local grid, and on sunny days, it can provide enough power to charge one EV. In [10], a study that was similar to [11] but used wind energy was suggested. The cost, validity, and utility of a grid-tied PV-Wind EVCS for stadiums were examined in [12]. It was found that the technique could lower CO2 emissions and was beneficial. A compact Tuk-Tuk PV-wind charging station has been designed in a similar manner, although diesel generation has not been taken into consideration. In [13-14], various generating choices, including PV, diesel generating, and storage

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batteries, were taken into consideration while an ideal EVCS architecture was examined. The wind, however, was not regarded as a possibility. The economic and environmental effects of two incidents have been examined. Both of the scenarios used grid-connected and isolated EVCS.

It is obvious that further research and analysis are still needed in this field. What was done in [15] will be improved upon by the work that will be covered in this paper. In [15], a hybrid EVCS system was studied with limited consideration of renewable resource combinations. This work's primary contribution will be as follows:

(i) Examining and evaluating hybrid stand-alone systems from an economic, technological, and environmental aspect.

(ii) Evaluating different system configurations and suggesting optimal sizes for various hybrid components.

The selection of the EVCS location plays a significant role in system performance, as solar irradiation, wind availability, and load characteristics directly influence system design and economic outcomes. Therefore, site-specific analysis is essential for accurate assessment.

2 SELECTED SITE DESCRIPTION

In this study, Bengaluru, in India with solar irradiation of 5.32 kWh/m2/day (annual average) and with wind0speed of 3.67 m/s (annual average) condition is selected as shown in Figure 1 and Figure 2.

Karnataka, located in the southern part of India between latitudes 11.5°N to 18.5°N and longitudes 74°E to 78.5°E, is bordered by the Arabian Sea to the west, Maharashtra to the north, Andhra Pradesh and Telangana to the east, and Tamil Nadu and Kerala to the south. Karnataka state's capital and commercial and cultural hub is Bengaluru (see Figure 1). According to Köppen's climatic classification, it has a tropical savanna climate with distinct wet and dry seasons. Bengaluru typically experiences a more temperate climate all year round because of its high elevation; January is the coolest month, with an0average low temperature0of 15.1 °C (59.2 °F), and April is the hottest, with an average0high temperature of 35 °C (95 °F). 39.2 °C is the hottest0temperature ever recorded in Bengaluru. There are 8.5 million people living in Bengaluru (Census Organisation of India 2011). Figure 1 illustrates that the average monthly solar global horizontal irradiance in Bengaluru, based on HOMER data and representing monthly averages, is 5.26 kWh/m20day. March has the most radiation (6.56 kWh/m2 day), while August0has the lowest (4.47 kWh/m2 day).

The average monthly wind speed in the given area is presented by the wind resource. Data input is displayed as the average monthly wind speed for the Karnataka months of January through December in Fig. 2. January is the month with the lowest wind speed, while June and July have the highest. The data used for solar irradiation and wind speed are obtained from the HOMER software database, which retrieves long-term meteorological data based on the geographical coordinates of the selected site, ensuring reproducibility. Although this study considers a single site (Bengaluru), it is used as a representative case to demonstrate the proposed methodology. The approach can be extended to multiple locations for comparative analysis in future work.

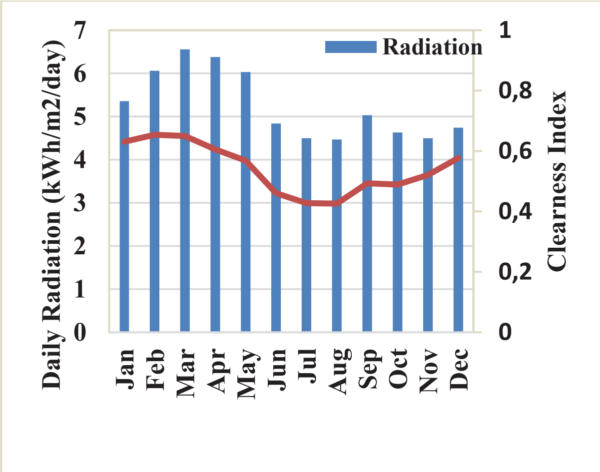

Fig. 1. The average solar global horizontal irradiance in Karnataka

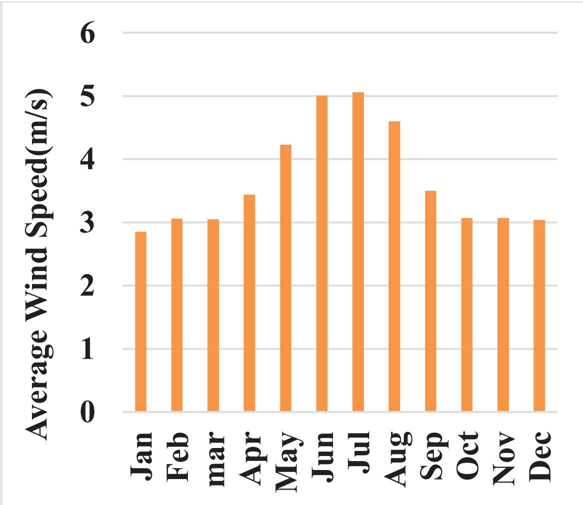

Fig. 2. Average Wind Speed in Karnataka

3COMPONENTS OF THE HYBRID EV CHARGING STATION

3.1.Configuration and Working Principle

In this section the different designs of EVCS are examined. Three cases are considered, Diesel Based EVCs, Renewable Based EVCS the isolated EVCS, and Diesel-Renewable Based EVCS. The aim is to design EVCS as efficiently as possible while minimising lifecycle costs, accounting for environmental emissions, and taking into account different energy supply choices. It is assumed in this study that the EVCS is a standalone microgrid that is powered by diesel generators.

The sizing of the major system components, including the photovoltaic (PV) array, wind turbine, diesel generator, and battery storage, was carried out using the optimization capability of the HOMER software [15]. The model inputs consist of site-specific solar radiation and wind speed data, along with the load profile of the

EVCS. Resource data were obtained through HOMER by specifying the geographical coordinates of the selected location [15]. The capacity ranges for each component were selected based on values commonly reported in prior studies and supported by manufacturer specifications [9]-[13]. Economic parameters such as capital cost, replacement cost, operation and maintenance cost, and component lifetime were defined using standard values available in HOMER and supplemented with data from the literature [12]-[15]. HOMER evaluates multiple possible configurations and identifies the most suitable system based on performance indicators such as net present cost (NPC) and cost of energy (COE) [15]. The analysis assumes standard operating conditions and typical component efficiencies, allowing the methodology to be replicated for similar locations using equivalent input parameters [3], [4].

Optimal Plan Configurations:

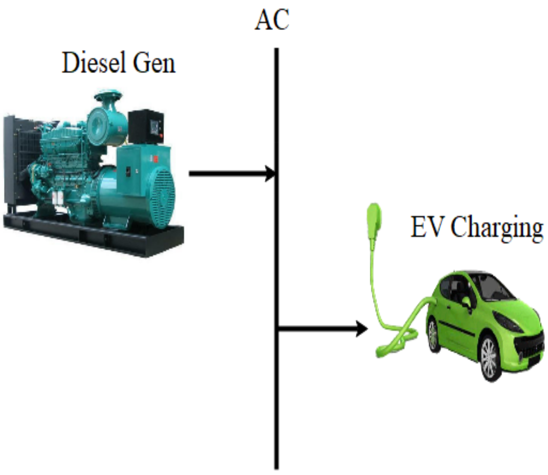

Fig.3. Diesel Based EVCS

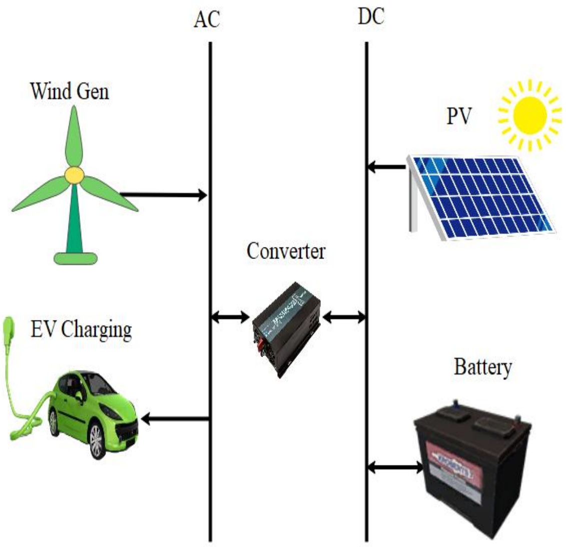

Fig.4. Renewable Based EVCS

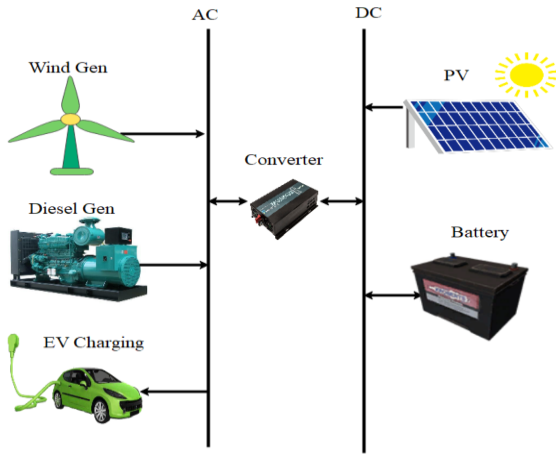

Fig.5. Diesel/Renewable Based EVCS

Table 1. Summary of Cases

Case	Description of Case
1	Isolated EVCS
2	Diesel Based EVCs
3	Renewable Based EVCS
4	Diesel-Renewable Based EVCS

Table 2. Cost Data of Energy supply Resources

Component	Capital Cost ($)	Replacement Cost ($)	O&M Cost
PV	3000	2500	50 $/year
Wind	7000	7000	80 $/year
Diesel Generator	2250	2250	0.15 $/h
Battery	550	550	10 $/year
Converter	300	300	--

Table 3. Sizing components and other parameters

Component	Options on Size and Unit Numbers	Life	Other Information
PV	10, 50, 100, 150, 200 kW	25 years	Derating Factor = 88%
Wind (10kW)	10, 20, 30, 40, 50 Units	20 years	Hub Height = 24m
Diesel Generator	10, 50, 100, 200, 500 kW	15,000 Hrs	Minimum Load ratio = 25%

Battery	50, 100,200, 500 Units	15 years	Nominal capacity = 167Ah, 24V
Converter	0, 10, 50, 100, 200, 500 kW	10 years	Converter Efficiency = 90% Rectifier Efficiency = 85%

The component ratings and cost parameters presented in Tables 2 and 3 are obtained from HOMER input data, which are based on standard manufacturer specifications and values reported in the literature.

4 RESULTS AND DISCUSSION

The principal EV charging hours are 8 a.m. to 5 p.m., as seen in Fig. 6, and the annual operational frequency of EV charging stations is 541 kWh/day. Lower charging frequencies are found at other times of the day, such as 6 a.m. to 7 a.m. and 6 p.m. to 12 midnight. The EVCS's situation is comparable to that of other EVCS load profiles reported in literature [6]-[8], particularly in terms of daily charging pattern and load distribution. For a certain EVCS, the demand for EVs is nearly stable throughout the year. The demand will be effectively met by the proposed stand-alone hybrid facility.

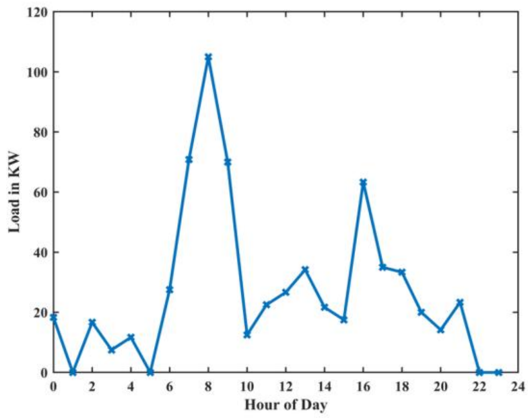

Fig.6. Daily Load Curve of the Proposed EVCS

Table 4. Optimal EVCS Design

Component	Case-1		
	(a)	(b)	(c)
Diesel(kW)	120	0	100
PV (kW)	0	120	30
Wind (kW)	0	80	50
Battery(numbers)	0	2000	400
Converter (kW)	0	200	100

The best configurations and design plans demonstrate that the renewable-based EVCS Case-1(b) only uses solar PV and wind power, in contrast to the diesel-reliant EVCS Case-1(a), which uses diesel production to meet its needs. The diesel-solar PV-wind combination EVCS Case-1(c) chooses some solar PV and wind capacity along with a lower diesel generation capacity.

The NPC, levelized COE, and O&M costs for each scenario are displayed in Table 5. Diesel-renewable EVCS is the best option for isolated EVCS since the NPC and levelized COE in Case-1(c) are much cheaper than in Case-1(a) and (b). This conclusion is based on the optimization results obtained from HOMER, as presented in Table 4 and Table 5, where the cost parameters (NPC, COE, and O&M) are computed for each configuration. The levelized COE is shown to be very high in both isolated and grid-connected EVCS Case-1(b) when the EVCS is only based on solar and wind due to the considerable capital cost component. Even while the levelized COE in the diesel-dependent EVCS is lower—it is 1.71 \$/kWh in Case-1(a)—it is still greater since the diesel-based EVCS has substantially higher fuel costs than the diesel-solar PV-wind combination.

4.1 Optimal Production and Consumption Patterns for Different EVCS Setups

Table 6 and Figs. 7, 8, and 9 present comparisons of electrical energy output and consumption for multiple scenarios. Table 6 shows that the solar PV, wind-based EVCS Case-1(b) produces substantially more energy overall than the other scenarios. The diesel-based EVCS Case-1(a) uses just diesel as a source of energy. In Case-1(c), renewable energy makes up 61% of the energy supply, with diesel accounting for the majority of the remaining energy.

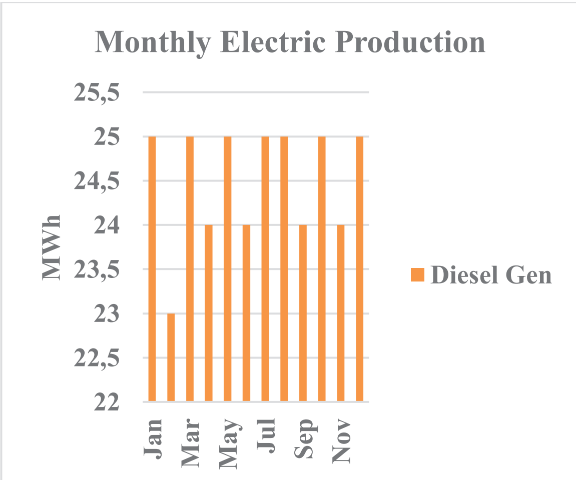

Fig.7. Diesel Based EVCS

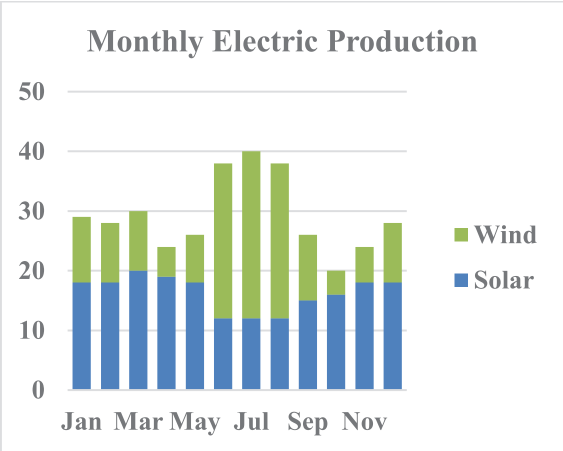

Fig.8 Renewable based EVCS

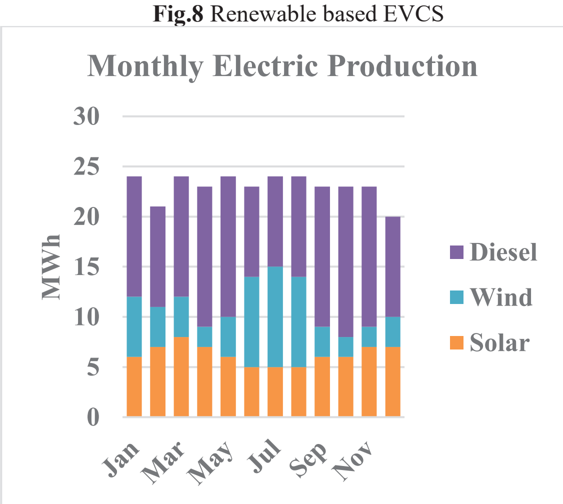

Fig.9. Diesel-Renewable Based

Table 5. Comparison of the Cost Elements

Components	Case-1 (a)	Case-1 (b)	Case-1 (c)
Net Present Cost, M$	5.27	2.33	1.91
Levelized COE, $/kWh	1.71	0.757	0.621
O & M Cost, M$/year	3,83,992	58,148	95,402

Table 6. Comparison of the Production and Consumption of Energy

	Case-1		
	(a)	(b)	(c)
Component			
Diesel	2,92,622 (100%)	--	1,33,485 (49%)
PV	--	1,88,106 (53.9%)	78,378 (28.8%)
Wind	--	1,61,104 (46.1%)	60,414 (22.2%)
Renewable Energy Contribution	0%	100%	61%
Total	2,92,622	3,49,210	2,65,593
EVCS Load Served	2,37,860	2,37,860	2,37,860
Excess Electricity	54,762	92,517	15,077

As mentioned before, one of the primary goals of this effort is to use green energy sources to reduce emissions. When compared to all other scenarios, the results in Table 7 show that the solar PV, wind, and BESS-based EVCS in example 1(b) greatly lowers the overall system emissions. When compared to the pure diesel-based option, the diesel-solar PV-wind mix is still more environmentally friendly even though it emits more than the solar PV-wind based alternative.

Table 7: Environmental Emissions Comparison of Different EVCS Configurations

Pollutant	Case-1		
	(a)	(b)	(c)
Carbon dioxide	2,19,385	0	90,370

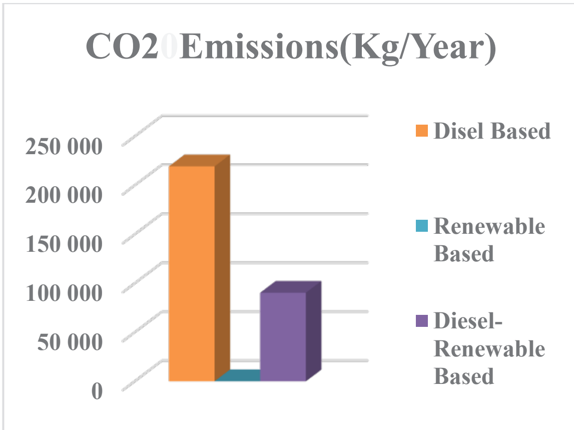

Fig.10. Comparison of CO_2 Emissions for different Systems

5 CONCLUSION

In this study, an optimal EVCS design configuration was examined. Numerous power sources were taken into consideration, including solar, wind, diesel generators, and batteries. HOMER software was used to conduct the analysis utilising various case studies. The findings show that the diesel renewable mix is the most cost-effective islanded EVCS. This approach is less polluting than diesel-based EVCS, although having higher emissions than renewable-based EVCS.

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