

Artificial Intelligence for Harnessing Hybrid Renewable Energy Systems for Efficient Electric Vehicle Charging Infrastructure in India

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Abstract— This manuscript explores the potential of renewable and hybrid renewable energy systems (HRES) in enhancing the efficiency of electric vehicle (EV) charging infrastructure in India. As the adoption of EVs rushes, the demand for sustainable and reliable energy sources becomes critical for integrating renewable energy sources into a grid. The paper examines the technical, economic, and environmental aspects of implementing HRES for EV charging. The findings suggest that with proper integration and policy support, renewable energy sources can significantly contribute to developing a sustainable EV ecosystem in India. This study includes simulation analysis of renewable sources, such as wind, and solar PV using the system advisor model (SAM) to demonstrate power generation and overall system performance. The later portion of the manuscript proposes the short-term prediction analysis of solar radiation. The paper also proposed the computation of LCoC (Levelized cost of charging) for Electrical Vehicles 350kW charging infrastructure. The LCoC continues values are proposed for 1MW installed capacity of solar PV and wind power plant. From the SAM software the computation of LCoE is taken after performing the simulation. Although this study is undertaken for India, but the proposed EV charging infrastructure methodology based on renewable energy resources may be adopted by other countries as well. The data set of solar radiation is generated from the SAM software for coordinates 23.2156° N, 72.6369° E is taken for prediction considerations. The prediction analysis for solar radiation has performed with the help of different artificial intelligence and machine learning algorithms. The prediction algorithms linear regression, random forest, support vector machine and decision tree are used in this work. The proposed comparative analysis suggested model accuracy. The best model is found out as an outcome of the manuscript.

Index Terms-- Electric vehicle, Energy storage system, Hybrid renewable energy system, Levelized cost of charging.

I. INTRODUCTION

The deteriorating energy availability, increasing environmental awareness, and the harmful consequences of

climate change demands renewable energy integration with electric vehicle (EV) technology with smart charging methods [1]. EVs powered by renewable energy sources can help to reduce greenhouse gas emissions from the transportation sector, which is one of the largest contributors to climate change [2]. In order to improve air quality in urban areas, EVs adoption can help in producing zero emissions [3]. The use of renewable energy sources for EV charging can help to reduce dependence on imported fossil fuels. A major need of reliable charging infrastructure can be addressed by including hybrid renewable energy systems (RES) along with grid-based charging stations, as RES are not affected by power outages or fluctuations in the grid [4]. Further, hybrid RES can help to reduce the cost of EV charging, as they can utilize lower-cost renewable energy sources. A thorough review of this topic can help to inform decision-makers about the potential benefits and challenges of using hybrid renewable energy systems for EV charging. This review examines the significance, benefits, and challenges associated with implementing hybrid RES-based EV charging stations, combining various renewable sources such as photovoltaic (PV) solar panels, wind turbines, bio-fuel generators, and advanced battery storage. Photovoltaic solar panels have emerged as a leading renewable energy technology, capable of converting sunlight directly into electricity. Integrating PV panels into EV charging stations can enable them to harness the abundant solar energy, reducing dependence on the grid and minimizing greenhouse gas emissions [5]. Challenges include intermittent energy production and seasonal variations, necessitating the use of battery storage systems for efficient energy management. Wind energy is another pivotal component of hybrid systems. Wind turbines can generate electricity by harnessing the kinetic energy of wind, making them an excellent complement to solar panels [6]. When combined with solar power in EV charging stations, wind energy can help balance energy fluctuations and contribute to more reliable charging infrastructure [7].

Challenges include the availability of suitable wind resources and addressing the intermittency of wind energy. Bio-fuel generators are a renewable energy option that utilizes organic matter, such as agricultural waste or purpose-grown crops, to produce electricity [8]. These generators can serve as a backup or supplementary power source for EV charging stations during periods of low solar or wind energy availability [9]. Though, concerns related to sustainability, land use, and competition with food crops must be addressed when considering bio-fuels as part of a hybrid system [10]. Advanced battery storage is a crucial element in HRES-based EV charging stations. It addresses the intermittent nature of renewable energy sources by storing excess energy during peak production times and releasing it during periods of high demand [11, 12]. Utilizing battery storage optimizes energy utilization, enhances grid stability, and improves the overall efficiency of the charging infrastructure. Nonetheless, battery cost, environmental impact, and recycling challenges are vital considerations. This manuscript provides valuable insights into the following domains:

- The scenario of Electric Vehicles in India.
- The types and technical feasibility of HRES for EV charging. Energy production from Solar and wind power plants.
- The economic viability of HRES for EV charging using System Advisor Model (SAM).
- Calculations of levelized cost of charging.
- Prediction analysis for solar radiation using advanced machine learning algorithms.

II. EV MARKET IN INDIA

There is a significant rise in EV market in India during last half a decade, i.e., in two wheelers, three-wheelers, and four wheelers. The statistical data talks about more than 950,000 EVs sold out during 2022. Similarly, there is a significant rise in the market during the calendar year 2023. Sales reached 1532386 units sold out with 55% growth rate. The bifurcation of EV sold out in 2023 is shown in fig. 1 [13]. Fig. 1 showing the relevant data for the financial year. More than 2000 EV buses are running to date in India. Considering, 2024 hits the growth rate of 27% over the previous year. The total of 1949114 units were sold out. The electric vehicle (EV) market in India is steadily growing, with several manufacturers offering a range of options across different vehicle segments. The comparative table of year wise EV sale is shown in table I.

TABLE I. EV SALES SCENARIO IN INDIA DURING LAST DECADE

Sr. No.	Calendar year	Number of units of EV sold in India
1	2015	11850
2	2016	53025
3	2017	89386
4	2018	126569
5	2019	162617
6	2020	120996
7	2021	327644
8	2022	987000
9	2023	1532386
10	2024	1949114

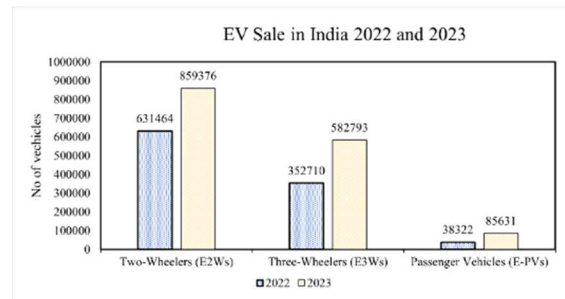


Figure 1. EV Sales in India during calendar year 2022 & 2023 [13].

III. STANDALONE AND GRID CONNECTED HRES

The HRES integrates solar PV, wind power systems, and other renewable resources, offering a promising solution to meet the load demand while reducing reliance on conventional energy.

A. HRES, Microgrids and Energy Storage with its importance

The terminology related to HRES is microgrid. Both the concepts aim to improve the efficiency and sustainability of energy generation and distribution, they serve different purposes and have distinct characteristics. However, the main difference between microgrid and HRES is as follows [14]:

(1) A HRES is primarily concerned with optimizing renewable energy sources to produce clean electricity, while a microgrid focuses on localized energy management and resilience, being able to operate both connected to an isolated from the main power grid. (2) HRES are typically installed at a larger scale, often in industrial settings or remote areas where a reliable power supply is required according to power demand. They are more suitable for meeting the energy needs of communities or facilities depending on power demand, while the microgrids are generally smaller in scale and are commonly implemented in local communities, military bases, universities, hospitals, or commercial/industrial complexes. Their focus is on serving a specific area or facility with more localized control over energy/power generation and consumption. The HRES defined as a system with more than one energy sources, with at least one renewable energy source (or multiple) and integrated with an energy storage system. The standalone HRES satisfies the demand using local generation from available energy sources. The hybridization is formed with different configurations and with inclusion of different configurations which are as follows. These systems have various configurations in line with the interfacing medium and type of the generation (AC/DC). Energy storage helps address these challenges and brings several important benefits to hybrid renewable energy systems [14]:

- **Storing Excess Energy:** Renewable energy sources often produce more power than is needed at a particular moment. Energy storage allows the excess energy to be stored for later use, avoiding wastage and making sure the generated energy is utilized effectively.
- **Supply Stability:** Fluctuations in renewable energy generation can lead to variations in power supply.
- **Load Balancing:** Energy storage facilitates load balancing by matching energy supply with demand.

- **Integration and Grid Support:** Energy storage systems enhance the integration of renewable energy into the existing power grid.
- **Time-Shifted Energy:** Energy storage enables time-shifting of energy production.
- **Backup Power:** Energy storage serves as a reliable backup power source in case of emergencies or when renewable energy sources are temporarily unavailable, ensuring continuous power supply and preventing disruptions.
- **Remote and Off-Grid Applications:** In remote areas or off-grid locations, energy storage systems are essential to store excess energy for periods when renewable sources are not available, reducing the dependency on fossil fuel-based generators.
- **Renewable Energy Penetration:** Energy storage enables higher penetration of renewable energy in the overall energy mix.

B. Realising HRES

The block diagram of wind energy conversion system, solar PV system and incorporation of energy storage is shown in fig. 2. The layout in Fig. 2 illustrates the setup of a HRES consisting of PV system and WECS connected to standalone loads with the BESS as a backup source. In this system, the primary sources of energy are the WECS and PV systems. To ensure a continuous power supply, a BESS is incorporated, which serves as a backup during early morning and late evening when the renewable energy sources might not be sufficient. Additionally, the BESS acts as a buffer during periods of low wind, stabilizing the system.

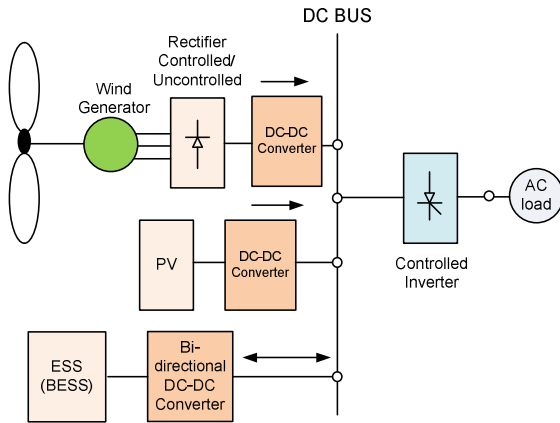


Figure 2. Schematic diagram for wind, solar PV and BESS based HRES.

C. HRES based EV charging:

Integrating a hybrid renewable energy system (HRES) into electric vehicle (EV) charging applications can enhance sustainability and reduce reliance on grid electricity. HRES combines renewable energy sources, such as solar PV panels, wind turbines, and energy storage systems (batteries and supercapacitors) to power the EV charging infrastructure. The insufficient charging infrastructure and the need for advanced energy storage technology primarily hinder the adoption of

electrified transportation with EVs. Integrating many EVs into the electrical grid could lead to significant strain on the existing infrastructure. To address these crucial issues, a comprehensive model for a hybrid renewable energy-based EV charging station is reported by Madhumitha et al. [15, 16] that incorporates a solar power generation unit, a wind turbine, and a fuel cell. The integration of an EV charging station with a hybrid microgrid system plays a crucial role in achieving efficient control and active power flow within modern distributed systems. However, the current approach to charging EVs in the microgrid system is cumbersome and heterogeneous, leading to inefficient utilization of renewable resources in certain critical situations. As the transition towards EVs gains momentum, charging stations are evolving with multiport configurations, introducing added complexity to the microgrid [17].

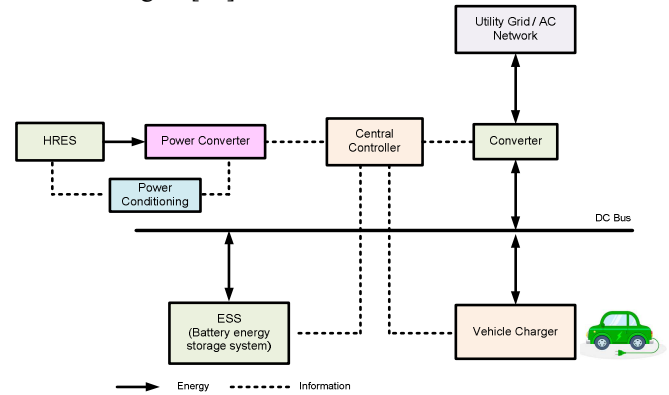


Figure 3. Interfacing HRES for EV charging applications.

Fig. 3 demonstrates the block diagram of HRES interfaced with EV charging infrastructure. The information and energy flow are shown in Fig. 3. The central controller is taking care of energy management which includes power conditioning, monitoring, state of charge of energy storage, power flow from source of HRES or grid, decision making algorithms etc. The information flow is shown with dotted lines and energy flow is shown with thick line [18]. The Storage systems (in present case battery energy storage systems) are crucial for maximizing the asset utilization and efficiency by serving as power back up during peak load situations in emerging microgrid energy management.

IV. SIMULATION RESULTS FOR SOLAR PV SYSTEM, WIND POWER SYSTEM AND LCoC FOR EV CHARGING

A. Simulation results for solar PV and wind power system.

The simulation analysis in SAM is performed for 1MW installed capacity solar PV and wind system. Fig. 4 and fig. 5 demonstrate the energy generation pattern for one year.

B. Computation of Levelised cost of charging for 350kW electrical vehicle:

The LCoC calculation is performed using (1), The levelised cost of charging (LCoC) represents the mean selling price for electricity needed to offset the overall production expenses

throughout the lifespan of a system. It serves as a valuable tool for investment strategizing and facilitates the comparison of various approaches to generating electricity. The mathematical equation given through (1) is used for the computation of LCoC [19, 20]. The case study is made for 350kW electrical vehicle charging infrastructure

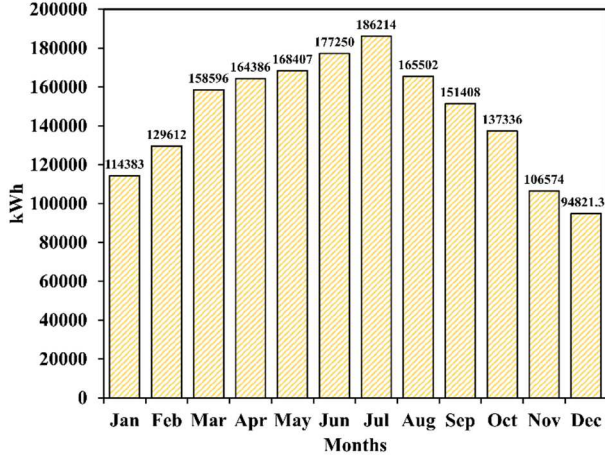


Figure 4. Energy generation from Solar PV system.

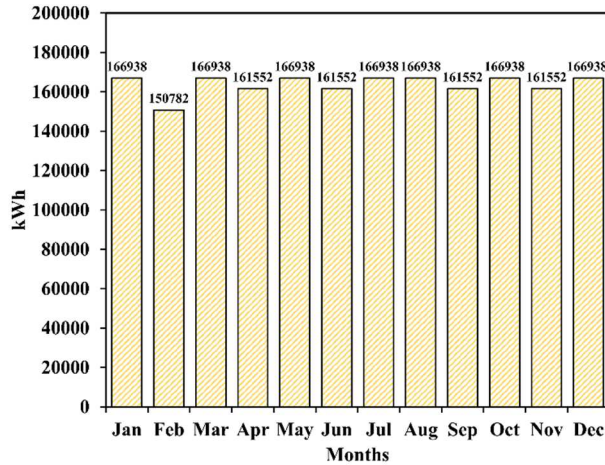


Figure 5. Energy generation from Wind power system.

$$LCOE = \left(\frac{C_{equi} + C_{install} + \sum_{t=1}^T \frac{C_{O\&M}_t}{(1+i)^t}}{\sum_{t=1}^T \frac{E_{charging}_t}{(1+i)^t}} + \frac{C_{electricity}}{\eta} \right) * (1 + C_{trans}) \quad (1)$$

where, C_{equi} is the cost of the charging equipment hardware (€/plug), $C_{install}$ is the cost of installing the charging equipment, (€/plug), $C_{O\&M}_t$ is the cost of operation and maintenance of the charging infrastructure in year t of the project's lifetime (€/year), $E_{charging}_t$ is the yearly amount of energy that is charged at the plug in year t of the project's lifetime (kWh/year), $C_{electricity}$ is the electricity cost (€/kWh), η is the charging station efficiency (%), C_{trans} is the transaction cost for settling the payment for the charging energy where applicable (%), T is the project life time over which the LCoC is calculated (years), and

i denotes the interest rate, used to discount future costs and energy to a net present value (reflecting the financing cost of charging station operators where applicable) (%). By considering charging station efficiency, the model considers charging losses in the charging equipment. The computation of LCoE is performed by using SAM model. The energy generation from 1MW_p solar PV power plant and 1MW installed capacity of wind energy conversion system are demonstrated in fig. 4 and fig. 5 respectively, simulated in SAM software. From the computed LCoE value for wind and solar power plants the LCoC from (1) is computed. The LCoE and the LCoC values are computed in table II. The remaining results computed from the SAM are tabulated in table III.

TABLE II. COMPUTATION OF LCOE AND LCOC

LCoE (Wind)	0.038 €/kWh
LCoE (Solar PV)	0.016 €/kWh
LCoC (Wind)	0.065 €/kWh
LCoC (Solar PV)	0.037 €/kWh

TABLE III. COMPUTATION PARAMETERS FOR SOLAR PV & WIND ENERGY CONVERSION SYSTEM

Parameter	Solar PV	Wind
Annual AC energy in year	1754491 kWh	1965555 kWh
Installed Capacity	1MW AC = 1250 MWp	1MW AC
DC Capacity factor in year	16.7% (DC)	22.4% (AC)

V. MACHINE LEARNING MODELS FOR PREDICTION OF RADIATION AND ITS ANALYSIS

The various machine learning models are studied and implemented to find out RMSE for solar radiation. The prediction variable is taken as solar insolation in W/m² for this work. The data set is generated and mined for the monthly basis for one year time. The ML algorithms used for this work include for prediction are linear regression, the random forest, the support vector machine and the decision tree. The modeling equations are described in brief as below:

A. Linear Regression

Simple linear regression is a supervised learning algorithm that models the relationship between a dependent variable and an independent variable by fitting a straight line to the observed data [21]. The equation representing this relationship is typically expressed in (2) -

$$y = \beta_0 + \beta_1 x + \epsilon \quad (2)$$

Where, β_0 is the intercept, β_1 is the slope of the equation, ϵ is the absolute error term.

B. Random Forest

The Random Forest regression is one of the algorithms that uses the ensemble learning method when it comes to regression. An ensemble learning method is basically a way of combining predictions from different machine learning algorithms together to make a better prediction than just one model which the random forest can perform [22, 23, 24].

C. Support Vector Machine

Support Vector Machine (SVM) is a very good machine learning technique applicable to both linear and non-linear-classification regression and outlier detection. It is correlated

with high flexibility, such that it is used extensively in such areas: text classification, image classification, spam detection, handwriting recognition, gene expression analysis, face recognition, and anomaly detection [25].

D. Decision Tree

A decision tree is a sophisticated machine-learning algorithm that plays a crucial role in predicting the value of a target variable by analyzing the values of other input variables. When dealing with a continuous target variable, the decision tree takes the form of a regression tree. This algorithm conducts a recursive process of segmenting the input data into smaller groups based on the values of the input variables [26]. Considering the present work, the above algorithms are proposed for solar insolation data. The root mean square error (RMSE) is found out for algorithm mentioned above and compared. The comparison is performed on a monthly basis by considering the data set of solar insolation for one year of the location 23.2156° N, 72.6369° E. The tabular in table IV form showcases the RMSE for LR, RF, DT, and SVM. The random forest algorithm is best suited for the data set like solar insolation for location. However, the comparative analysis shows the various RMSE for the twelve months of a year. The machine learning algorithms and their models could facilitate the calculation of solar PV insolation helps to identify the future insolation prediction for solar PV power generation. Fig. 6 to fig. 9 showing the output results of prediction for 4 prediction methods and the computed results are tabulated in table IV.

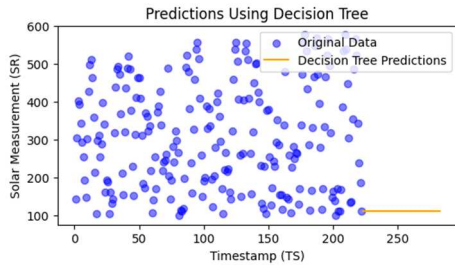


Figure 6. Prediction using Decision Tree algorithm.

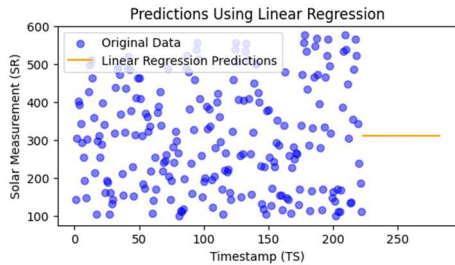


Figure 7. Prediction using Linear Regression algorithm.

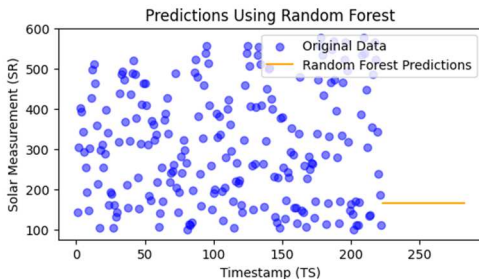


Figure 8. Prediction using Random Forest algorithm.

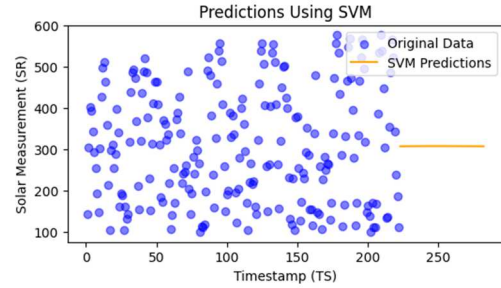


Figure 9. Prediction using Support Vector Machine algorithm.

TABLE IV. COMPARATIVE ANALYSIS OF RMSE FOR LR, RF, DT, SVM FOR SOLAR INSOLATION DATA

Month	LR	RF	DT	SVM
Jan	127.62	88.69	110.15	127.80
Feb	170.83	136.63	164.31	168.35
Mar	234.38	160.96	171.55	234.19
Apr	252.05	153.82	166.32	247.84
May	242.67	132.24	158.97	249.60
Jun	261.12	112.71	153.27	258.71
Jul	251.25	138.64	168.56	251.01
Aug	244.22	140.14	140.14	246.01
Sep	230.26	154.41	176.70	227.29
Oct	188.33	103.90	129.02	199.13
Nov	143.37	135.87	142.90	152.08
Dec	121.03	86.06	95.04	119.90

Potential pathways for futuristic approach comprise of formation of microgrid as a localized power generation medium for the locations which are far away from the grid integration point. The other critical aspects for the solar PV required little maintenance like periodic check of an inverter and proper cleaning of PV module is required. So, overall prediction values gives an idea about power generation for upcoming years.

CONCLUSION

The field of renewable energy, integration of energy storage and EV charging infrastructure evolve, some new challenges and the future directions having the potential to guide the development of efficient and adaptable HRES incorporating BESS for electric vehicle charging stations. The technological advancement to interface RES with the grid or BESS is discussed. The present study proposes the energy generation for solar PV and wind power system the highest energy generation is found in month of July where the daylight hours are more and pleasant atmospheric conditions. Through innovative solutions and continued technological advancements, these systems can contribute significantly to sustainable and resilient transportation infrastructure which leads towards overall cost reduction for LCoC. The LCoC is computed for solar PV and wind power plants. Lastly, the comparative analysis of machine learning algorithms gives an overview of RMSE and how the model is accurate as far as prediction is concerned. The random forest forecasting model is found suitable for this case study for the prediction of solar irradiation which leads the future direction of prediction of power generation.

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