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Research paper

Battery Charging Station for E-Bike Powered by A Vertical-Axis Wind Turbine

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Abstract

Nowadays, Electric Vehicles (EVs) are highly used due to increasing air pollution. In India, there are about 1742 EV charging stations, but EV sales are moderate due to the long charging time of EV batteries. To minimize the charging time, much research is underway. In order to solve that problem, part of the solution is Battery Swapping Stations (BSSs). Unfortunately, BSSs have many disadvantages. The proposed model of charging station is explained by the wind stand-alone partially discharged battery charging station, and it is being planned for the campus of the Coimbatore Institute of Technology (CIT), Coimbatore. Taking into account the available student and faculty time and wind power generation, this electric charging station has been designed. At night on CIT's campus, there is a high wind speed compared to the daytime, which occurs while the backup battery is charging. The backup battery keeps the system functioning. In the proposed system, a fuzzy logic controller is used to verify the operation of the charging station.

Keywords: *Battery Swapping Stations; Electric Vehicles; Fuzzy Logic Controller; Partially Discharged Battery Station; and Renewable Energy.*

1. Introduction

Charging stations provide electrical power for plug-in electric vehicles to charge their batteries. Electric vehicles are promising technologies for reducing emissions in global transportation, but the benefits depend on which sources of energy are used. Today, many EVs are powered by the thermal power grid [1]. For that, the concept of a fully green vehicle needs to change. EV charging stations are designed to draw power solely from renewable sources, making them truly green. The more renewable energy is used, the fewer charge points need to depend on the grid at all. The EVs can be charged without adding additional demand on the grid. With green power, electricity costs are lower and greenhouse gas emissions are cut, leading to a reduction in pollution [2]. Charging an EV with green power helps support renewable energy development and reduces the carbon footprint of purchasing electricity.

Rapid charging technology is needed to reduce the most prominent barrier for consumers to purchase EVs [3]. The DC fast charging method is fine, but it heats the battery significantly [4]. Consequently, regular rapid charging is degrading EV batteries in the long term [5]. EV charging is made easier by BSSs now. A fully charged battery can be easily replaced instead of an empty battery in EVs since owners aren't required to wait for battery charging. But some factors are affecting the battery swapping process, like battery capacity, various models of battery, and EVs [6]. As a result of the increase in the number of EV manufacturers, BSS has been unable to meet demand because it is not possible to manufacture universal model batteries [7]. The existing systems face challenges such as a lack of standardization, high infrastructure costs, and insufficient empirical validation of proposed smart swapping technologies. Additionally, they are limited by geographic dependence and the variability of wind resources, with little emphasis on energy storage solutions and economic viability.

In order to overcome the drawbacks of the BSS, a new type of battery charging station is needed, as well as the fact that electric vehicles are charged using fully green energies [8]. The partially discharged renewable energy-based battery charging station is proposed for charging EVs quickly and getting powered by wind sources. Wind energy is available throughout the day, and its energy is either minimal or maximal but never zero [9]. The EV batteries' charging time depends on wind speed. Based on wind energy, this model simulates the setup of a charging station for EVs.

The proposed method combines wind energy with the charging of partially discharged batteries, using a fuzzy logic controller to optimize performance according to wind availability and user schedules. Unlike existing systems that primarily analyze wind resources for direct EV charging, this model incorporates backup batteries and intelligent control to enhance reliability, particularly during stronger nighttime winds. In contrast to conventional battery swapping approaches, the CIT system prioritizes renewable energy utilization and partial battery charging instead of quick battery exchanges. Although the CIT model demonstrates potential for campus-level deployment, its dependence on local wind conditions and fuzzy logic calibration could restrict its broader application.

2. Materials and methods

2.1. Preprocessing of CIT campus wind data

The proposed off-grid EV charging station is powered by renewable energy. Wind is considered a renewable energy source. Locate the off-grid charging station before checking the availability of renewable resources [10]. An initial processing step is to measure the wind available at the CIT campus.

Fig. 1: Vantage Pro-2 Wireless Weather Station Placed at CIT Campus.

The CIT campus is in the Coimbatore district and Tamil Nadu state. Coimbatore has a pleasant climate. CIT campus is situated in Tamil Nadu, the southern part of India, at a latitude of 11° 01’ 39’’N, longitude of 77° E 01 37’’ and elevation 460 m. The monthly mean temperature, annual mean temperature, annual mean humidity, and average wind speed of the CIT campus are measured by a wind anemometer in Figure [1], and the data of the weather monitoring system covers about one year. This wind anemometer is located on terrace of library block, CIT campus and it contains a wind speed and direction sensor, 3 cup conical type, measuring range of 1~322km/h, accuracy of +/-3km/h, operating temperature - 40~65 degree Centigrade, 0~360degree designed by solid state magnetic sensor with UV resistant ABS body & holding part of anodized aluminium, supplied with cable & mounting arrangements, excitation voltage of 3V DC sourced from signal conditioner unit.
The wind speed is measured every half-hour interval, and Table [1] consists of one year of wind speed data for the CIT campus.

Table 1: Wind Speed Data of CIT Campus for One Year (Year: 2023)

Month	Average wind speed (m/s)
January	4.59
February	4.72
March	5.17
April	5.47
May	4.74
June	4.93
July	5.12
August	5.98
September	5.87
October	5.68
November	5.77
December	5.52
Average wind speed of one year	5.27

CIT's campus experiences an average wind speed of 5 m/s, as indicated in the above table.

2.2. Selection of wind turbine and generator

In a wind energy conversion system, wind speed is a very significant parameter [11]. The CIT campus has a relatively low average wind speed. A Vertical Axis Wind Turbine (VAWT) generates high electrical power from low wind speeds. VAWT is a reliable choice for standalone applications [12]. Table [2] describes VAWT.

Table 2: Specification of VAWT

Parameters	Range
Rated power	1 kW
Maximum output power	1500 W
Output voltage	48/ 110 V
Rotor height	2.8 m
Rotor diameter	2.0 m
Start-up wind speed	1.5 m/s
Rated wind speed	10 m/s
Survival wind speed	50 m/s
Off-grid voltage	48 V
Maximum rotating speed	300 rpm

The wind power is calculated by the following equation 1 [16]. The average wind power of the CIT campus is approximately 521 watts, as seen in Table [3]. For this reason, 1 kW VAWT is chosen. The wind speed on the CIT campus is much higher than the cut-in wind speed of VAWT (1.5 m/s), and it generates a lot of electricity.

$$\text{Wind power} = \frac{1}{2}\,\varrho\, A\, v^3 \quad \text{in Watts} \tag{1}$$

ϱ – Air density (kg m^{-3}); A – Swept area (m); v – Wind speed (m/s)

Table 3: Average Wind Power of CIT Campus

Month	Average Wind Speed (m/s)	Wind power (W)
January	4.59	331.69
February	4.72	360.68
March	5.17	473.99
April	5.47	561.38
May	4.74	365.28
June	4.93	410.99
July	5.12	460.37
August	5.98	733.50
September	5.87	693.76
October	5.68	628.55
November	5.77	658.90
December	5.52	576.91
Average wind power		521.33

The first step in converting wind energy into mechanical energy is done by VAWT. The next step is to convert mechanical energy into electric power using an affordable, efficient, and reliable generator. Permanent Magnet Synchronous Generator (PMSG) is the most appropriate choice for VAWT [13]. Using the gearbox in low wind speed applications is difficult, and the gearbox's efficiency reduces its output power. Hence, the direct drive method is advantageous, but this method is not applied to conventional high-speed electric machines. So, PMSG is more suitable for gearless applications [14]. The constant loss (mechanical loss and iron loss) of PMSG is negligible since the rotor is a permanent magnet. Also, copper loss is very low [15].

2.3. Methodology

The charging station is designed to use wind energy only. Based on the available wind speed at CIT, a charging station is created only for E-bikes. The 48V E-bike is suitable for that charging station. The E-bike parameters are listed in Table [4].

Table 4: Parameters of E-Bike Model

Battery capacity	1.2 kWh, 48V, 25 Ah
Driving range	75 km / Charge
Top speed	25 km
Normal charging time	2.45 hrs to 3 hrs

First, find out the Charging Time Demand (CTD) of the proposed model of E-bike and which is calculated by the following formula.

$$\text{Charging Time Demand} = \frac{\text{Vehicle battery capacity (kWh)}}{\text{Charging station rate (kW)}} \tag{2}$$

Table 5: CTD Calculation of E-Bike Charging from Wind Turbine

Wind power (W)	CTD of 25%	CTD of 50%	CTD of 75%	CTD of 100%
331.69	55min	1hr 49min	2hr 44min	3hr 37min
360.68	50min	1hr 40min	2hr 30min	3hr 20min
473.99	38min	1hr 16min	1hr 54min	2hr 32min
561.38	32min	1hr 4min	1hr 36min	2hr 8 min
365.28	50min	1hr 39min	2hr 29min	3hr 17min
410.99	44min	1hr 28min	2hr 12min	2 hr 55min
460.37	40min	1hr 19min	1hr 59min	2hr 37min
733.50	25min	49min	1hr 14min	1 hr 38min
693.76	26min	52min	1hr 18min	1 hr 44min
628.55	29min	58min	1hr 27min	1 hr 55 min
658.90	28min	55min	1hr 23min	1hr 49 min
576.91	32min	1hr 3min	1hr 34min	2hr 5min

Fig. 2: Block Diagram of the Off-Grid Charging Station Powered by Wind Energy without Backup Battery.

From Table [5], the power-up time of an E-bike is dependent on the wind power available and the power needed by the vehicle. In times of increased charging needs, the demand for charging time is high. It takes half an hour to recharge a minimum of one vehicle. Figure [2] contains a backup battery. This type of charging station is not suitable for charging many vehicles. As a result, the backup battery aids with the charging process and reduces the recharging time demanded by the vehicle, as shown in Figure [3]. The backup battery parameters are listed in Table [6].

Table 6: Specification of Backup Battery

Parameters	Ratings
Capacity	4.8 kWh
Voltage	48 V
Current	100 Ah

Fig. 3: Block Diagram of the Off-Grid Charging Station Powered by Wind Energy with Backup Battery.

Table 7: CTD Calculation of E-Bike Charging from Backup Battery

Backup battery status	CTD of 25%	CTD of 50%	CTD of 75%	CTD of 100%
Full	4 min	8 min	12 min	15 min
Three-quarter	5 min	10 min	15 min	20 min
Half	8 min	15 min	23 min	30 min
Quarter	15 min	30 min	45 min	1 hr

Table [7] shows that CTD is very low and E-bikes charge very quickly. After one or two vehicles are charged, the backup battery quickly dries out while it is continuously loading and discharging [7]. This is not healthy for backup battery performance, and its charging from Table [8] takes a long time. In Figure [4], the following model overcomes the above two models' shortcomings.

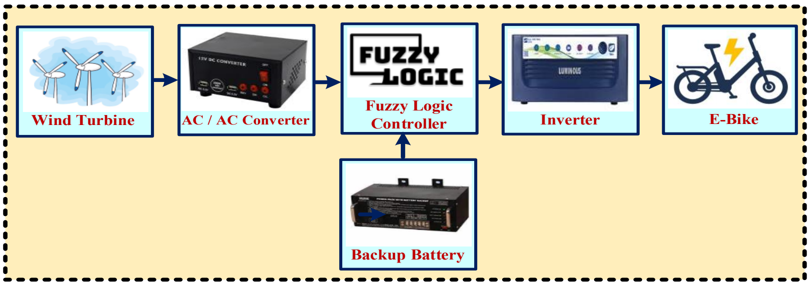

Fig. 4: Proposed Block Diagram of the Off-Grid Charging Station Powered by Wind Energy with Fuzzy Controller.

Table 8: CTD Calculation of Backup Battery Charging from Wind Turbine

Wind Power (W)	CTD of backup battery (100%)	CTD of backup battery (75%)	CTD of backup battery (50%)	CTD of backup battery (25%)
331.69	14hr 38min	10hr 59min	7hr 19min	3hr 40min
360.68	13hr 19min	10hr	6hr 40min	3hr 20min
473.99	10hr 8min	7hr 36min	5hr 4min	2hr 32min
561.38	8hr 33 min	6hr 26min	4hr 17min	2hr 9min
365.28	13hr 8min	9hr 51 min	6hr 34min	3hr 17min
410.99	11hr 41min	9hr 17min	6hr 11min	3hr 6min
460.37	10hr 26min	7hr 50min	5hr 13min	2hr 37min
733.50	6hr 32min	4hr 54min	3hr 16min	1hr 38min
693.76	6 hr 55min	5hr 12min	3hr 28min	1hr 44min
628.55	7hr 38 min	6hr 12min	4hr 8min	2hr 4min
658.90	7hr 17 min	6hr 4min	3hr 47min	2hr 17min
576.91	8hr 19min	6hr 15min	4hr 10min	2hr 5min

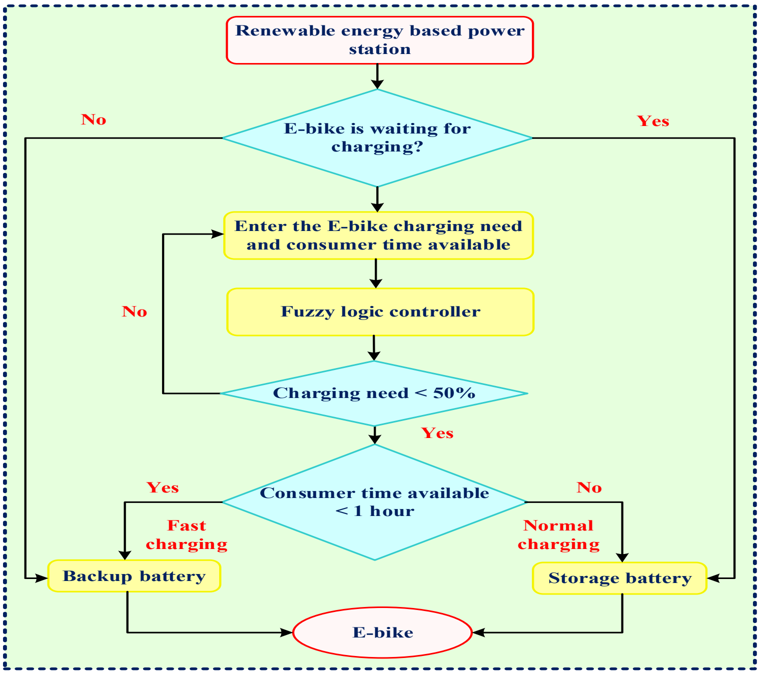

Fig. 5: Flow Chart of the Proposed Model.

This model of wind-powered off-grid charging station is based on consumer time availability, charging time, backup battery life, and e-bike battery performance. It provides both power points for storage and backup batteries. So, E-bikes can be powered at both points at the same time. The backup battery takes a long time to charge. At night time no one comes to charge, the backup battery is charging, and the wind speed is high. During the morning hours, the E-bike is connected to the backup battery for fast charging, and if the consumer has more time to wait, it is connected to the storage battery for slow charging. If no vehicle is present in the morning, the backup battery is connected to a wind turbine for power, and it is explained in Figure [5].

2.4. Fuzzy controller

The fuzzy logic controller is addressed in this work. Fuzzy logic controllers handle fluctuating inputs like wind speed and variable EV charging demands without needing precise input values. Unlike traditional PID controllers, fuzzy controllers function effectively without a detailed mathematical model. The rule-based structure allows for straightforward modification and expansion, making fuzzy logic suitable for managing complex, multi-variable energy systems. It is applied to four selection criteria, which are CS power available, backup battery status, E-bike charging needs, and consumer time available [2]. All four of these criteria need to be fuzzified to prevent backup batteries from charging and discharging simultaneously. Each criterion is assigned a membership function as shown in Figure [6].

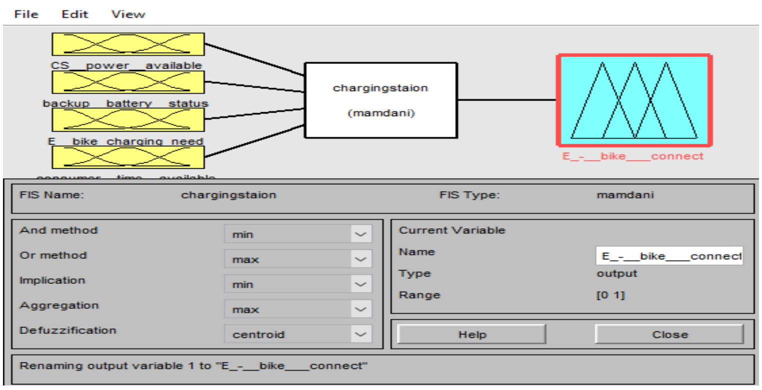

Fig. 6: Membership Function of Fuzzy Logic Controller.

Membership function for four criteria

1) CS power available: It is formed by the average wind power.

Less than Pavg and greater than Pavg.

2) Backup battery status: It is formed by the charging percentage of the backup battery.

Quarter, half, three-quarter, and full.

3) E-bike charging needs: It is formed by the percentage of vehicle battery charging needs.

Quarter, half, three-quarter, and full.

4) Consumer time available: It is formed by the consumer how much time to stay in the CIT campus.

Quarter hour, half hour, and one hour.

Membership function for output criteria

5) E-bike connect: It is formed by depending on the above four criteria.

Backup battery, wind turbine, and re-enter charging are needed.

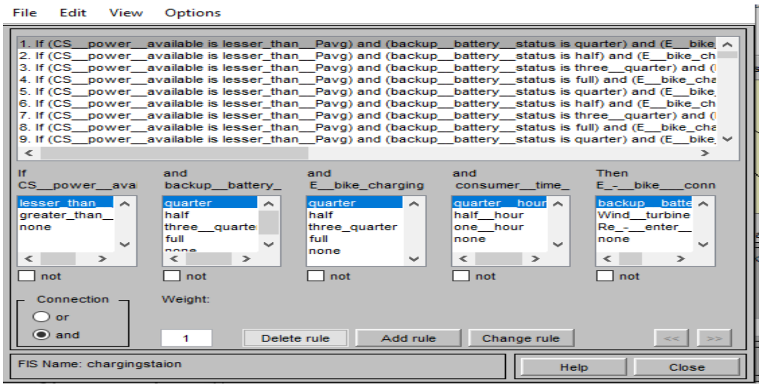

Fig. 7: Formation of Fuzzy Rules for Improving Efficiency of Charging Stations.

Rule 1:If (CS_power_available is lesser than_Pavg) and (backup_battery_status is quarter) and E_bike_charging_need is quarter) and (consumer _time_available is quarter_hour) then (E-bike _connect is backup_battery)

Similarly, 96 rules are framed for optimizing the performance of charging stations, as seen in Figure [7].

3. Results and discussion

The final output of the fuzzy logic controller is fuzzified from the four input membership functions. The fuzzy output indicates which connection to make between the E-bike and the backup battery or wind turbine. This suggestion is very helpful for avoiding continuous charging of backup batteries, and for charging two vehicles at once. It also helps prevent the rapid discharge of the backup battery.

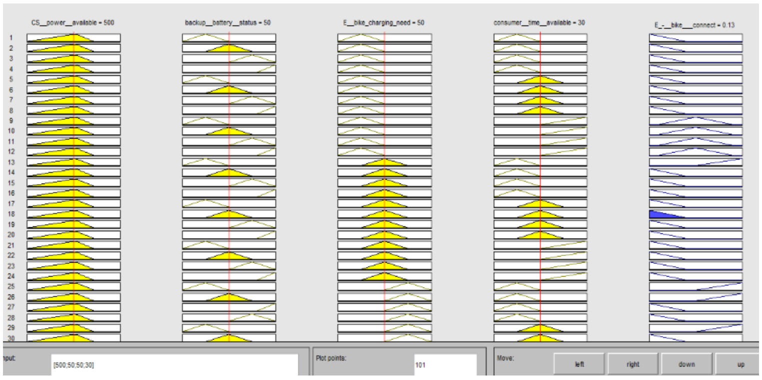

Fig. 8: Result of Fuzzy Controller.

In Figure [8], the wind power available is 500 W, the backup battery status is 50%, the E-bike charging need is 50%, and the consumer time available is 15 minutes. In this case, the fuzzy logic controller decides to make the connection between the E-bike and the backup battery. Hence, consumers wait for minimal amounts of time, and charging needs are halved. Meanwhile, the turbine output is lower, while the back power is 50%. In this situation, connecting the vehicle to a backup battery is the right decision.

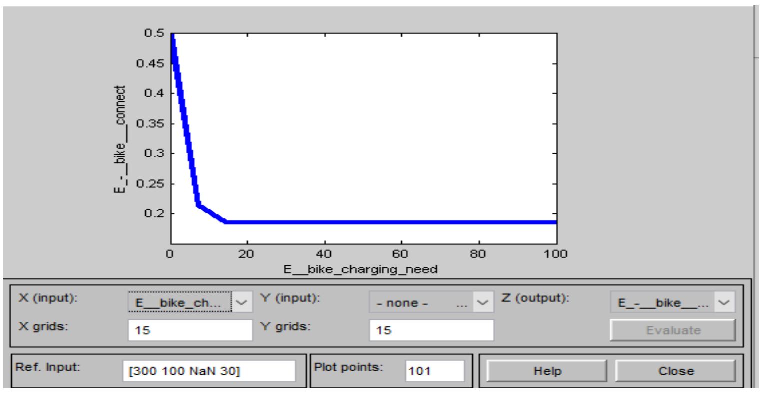

Fig. 9: Response of E-Bike Charging Need at Low Power Generation and Fully Charged Backup Battery.

A typical E-bike is used for short trips, such as commuting from home to the market, grocery shop, mall, workplace, or school. Most of the places listed above are within 10 to 20 kilometers of home. A typical E-bike can travel up to 100 to 120 kilometers on a full charge. A half charge is sufficient for frequent trips. From Figure [9], in the case of a full backup battery, the charging requirement is not an issue at this stage of low power generation. However, the backup battery status is also low, and the charging need parameter is very relevant. In Figure [10], if charging needs exceed 50%, output is greater than 0.5 (re-enter charging need). In that case, a charging station that covers less than 50% of the charging requirements will be efficient.

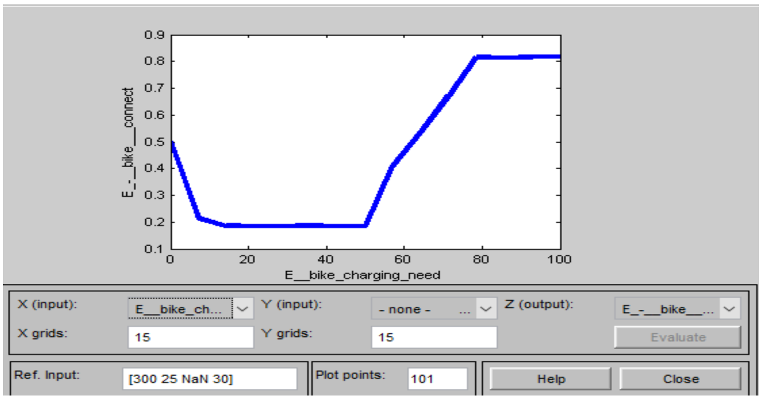

Fig. 10: Response of E-Bike Charging Need at Low Power Generation and Quarter-Charged Backup Battery.

In the same situation, having more time available is beneficial to better battery performance. Fast charging is not possible in that situation. The proposed charging station's highest consumer waiting time is one hour, providing a vehicle recharging time that does not exceed one hour. According to Figure [11], if the vehicle charging time is exceeded by one hour, the fuzzy output indicates a new charging need. Wind turbines and backup batteries will be more efficient if charging requirements can be reduced.

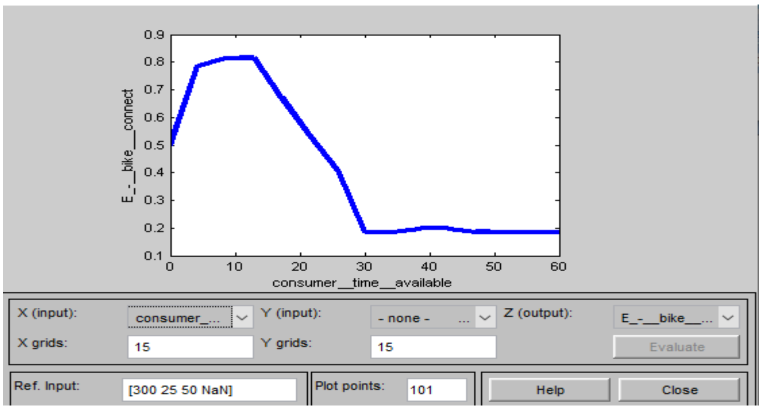

Fig. 11: Response of Consumer Time Available at Low Power Generation and Quarter-Charged Backup Battery.

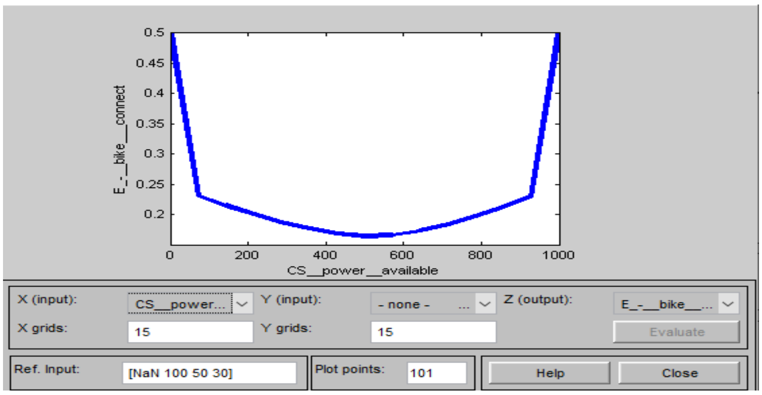

Fig. 12: Response of Charging Station Power Available at Fully Charged Backup Battery and Half-Hour Waiting Time.

If wind power generation is high, the vehicle is connected to a wind turbine for power; otherwise, it is connected to a backup battery. This is explained in Figure [12]. In the proposed charging station model, wind power generation is the main consideration, as well as vehicle charging needs. Using this type of charging station, 50% of the powering needs of vehicles can be met, and the average wind power output is maintained.

The main advantage of fuzzy logic applications in EV charging is their ability to handle uncertainties and dynamically optimize charging processes in real time. This leads to improved energy efficiency, better grid stability, and more effective integration of renewable energy sources. Consequently, fuzzy logic enhances the overall reliability and adaptability of EV charging systems.

The fuzzy logic controller efficiently manages connections between the E-bike, backup battery, and wind turbine based on real-time conditions to optimize charging. It prevents continuous backup battery use and supports charging multiple vehicles simultaneously. The system adapts to varying wind power, battery status, and user availability, ensuring minimal wait times. Wind power is prioritized when available, reducing dependency on backup batteries. Overall, the model balances energy sources to meet around 50% of vehicle charging needs efficiently. The proposed wind-powered EV charging station tackles long charging times by utilizing higher nighttime wind speeds on the CIT campus to enhance sustainability and reliability. A fuzzy logic controller manages fluctuating wind power and user demand, optimizing battery efficiency and system stability. This model reduces dependence on battery swapping, lowers operational issues, and supports environmental goals by using renewable energy. Its adaptability to uncertainties makes it robust and efficient. Overall, the system offers a scalable, practical solution for improving EV charging infrastructure.

4. Conclusion

Unfortunately, sometimes overcharging occurs, and precautions are not followed when recharging E-bikes at home. Improper charging is very dangerous for battery life, and sometimes the battery will be damaged. It is very dangerous for the person driving the vehicle. Charging stations face these problems by avoiding overcharging and checking the battery status of the vehicle before charging. During the charging process, the type of battery model and capacity of batteries are not considered since battery swapping has not taken place. Charge time for e-bikes is reduced due to charging only when they need it, and the stability of the power station is improved as a result. The backup battery is used to speed up charging for urgent trips.

The last one-year wind availability data was taken on the CIT campus with an anemometer. With the wind power available on the CIT campus, the charging station model is created and validated using a fuzzy logic controller. Specifically, the proposed model charging station is designed to meet 50% of the charging needs; it is targeted at extending the battery life of vehicles. Finally, the wind-powered charging station has overcome all the problems encountered. Future work involves integrating solar energy with wind energy to enhance the performance and reliability of the off-grid EV charging station.

- **Statements and declarations**

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

- **Statement of novelty and a statement of industrial relevance**

The proposed work introduces an innovative approach to sustainable and independent EV charging. Unlike conventional grid-dependent charging stations or solar-based solutions, this system leverages standalone wind energy, particularly utilizing the higher nighttime wind speeds at the Coimbatore Institute of Technology (CIT) campus. A backup battery system also ensures continuous operation, addressing intermittency issues associated with renewable energy sources. Integrating a fuzzy logic controller enhances the efficiency and adaptability of the charging process, optimizing energy utilization and ensuring a stable power supply. This novel combination of wind-based charging, intelligent energy management, and off-grid capability contributes to a more sustainable and efficient EV charging solution.

The Battery Charging Station for E-bikes Powered by a Vertical Axis Wind Turbine is highly relevant to the EV and renewable energy industries, offering a sustainable and decentralized charging alternative. With the increasing adoption of Electric Vehicles (EVs) and the growing demand for clean energy solutions, this system provides a cost-effective, off-grid charging solution, reducing dependence on fossil fuels and conventional power grids. Vertical Axis Wind Turbines (VAWTs) make it viable for urban and campus environments, where space constraints and unpredictable wind patterns pose challenges for traditional horizontal-axis wind turbines. Moreover, the intelligent fuzzy logic-based energy management system enhances the station's adaptability, making it suitable for diverse geographical locations. This innovation has the potential to be scaled for commercial applications, promoting widespread adoption of renewable-powered EV infrastructure and contributing to a greener transportation ecosystem.

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