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RESEARCH ARTICLE

Energy Management System for Hybrid Renewable Energy-Based Electric Vehicle Charging Station

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ABSTRACT This paper introduces an energy management algorithm for a hybrid solar and biogas-based electric vehicle charging station (EVCS) that considers techno-economic and environmental factors. The proposed algorithm is designed for a 20-kW EVCS and uses a fuzzy inference system in MATLAB SIMULINK to manage power generation, EV power demand, charging periods, and existing charging rates to optimize real-time charging costs and renewable energy utilization. The results show that the proposed algorithm reduces energy costs by 74.67% compared to existing flat rate tariffs and offers lower charging costs for weekdays and weekends. The integration of hybrid renewables also results in a significant reduction in greenhouse gas emissions, with payback periods for charging station owners being relatively short, making the project profitable.

INDEX TERMS Electric vehicle, electric vehicle charging station, fuzzy logic, renewable resources.

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations	**Full meaning**
EVCS	Electric Vehicle Charging Station.
GHG	Greenhouse Gas.
SMPS	Switch Mode Power Supply.
BRTA	Bangladesh Road Transport Authority.
BERC	Bangladesh Energy Regulatory Commission.
IDCOL	Infrastructure Development Corporation Ltd.
SOC	State of Charge of EV Battery.
Symbols	**Meaning**
P_{Gen}	Generated Power from Solar and Biogas.
s	Solar Irradiation in kWh/m^2/day.
w	Waste input in kg.
T_D	Duration of Charging.
C_{Batt}	EV Battery Capacity.
η	Efficiency of EV Charger.
L_{Ch}	Charging Level.
P_{EVCS}	Total Power Demand of the EVCS.
T_{Start}	EV Plug-in Time.
T_{Stop}	EV Disconnection Time.
T_w	Waiting Time.
T_C	Period of Charging.
$r(t)$	Existing Charging Tariff.
C_{cap}	Capital Cost.
C_{rep}	Replacement cost.
$C_{o\&m}$	Operation and maintenance cost.
PBP	Payback period.

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T	Lifetime in years.
C_{kWh}	Conventional electricity price in kWh.

I. INTRODUCTION

The rapid increase in the global electricity demand has led to the exploitation of fossil fuel resources and adversely affected environmental conditions, resulting in global warming. Apart from the energy sector, the transportation industry contributes significantly to worldwide greenhouse gas (GHG) emissions due to increasing fossil fuel consumption [1]. The governments of several countries are attempting to convert conventional transportation systems into green transportation systems using electric vehicles (EVs), which provide various socio-economic and environmental benefits. However, although these EVs do not directly consume fossil fuel resources, the electricity supplied from the fossil fuel-based electricity distribution grid indirectly increases their fossil fuel consumption. Therefore, to bridge the gap between electricity demand and supply, researchers worldwide aim to develop alternative renewable resources that are economical and eco-friendly [2], [3].

Furthermore, the rapid implementation of EVs as a cheaper mode of transportation, especially in developing countries, is limited by the lack of charging stations. Consequently, EV owners recharge the EV batteries from the residential connection, which presents a considerable system loss in the power sector and leads to a decreased profitability index [4]. Additionally, many EV chargers present power quality problems connected to the distribution grid, such as voltage fluctuations, harmonics, and power loss owing to their non-linear behavior [5]. These power quality problems within the distribution network are attributed to uncoordinated and inefficient EV charging schemes [6]. These can be solved by redesigning charging patterns [7], improving converter topologies [8], integrating renewable resources [9], and utilizing energy management approaches [10]. Utilization of the available renewable resources is considered the best approach from techno-economic and environmental perspectives. It also reduces the pressure on the utility grid, improving power quality [11], [12].

Despite the high capital requirement and intermittent properties of the renewable power-generation infrastructure, these resources have gained considerable importance since they are cost-effective, environment-friendly, and require low maintenance [13]. However, renewable integration for EV charging reduces the reliability and security of the systems due to the variability and uncertainty of renewable power generation. These limitations can be overcome by implementing hybrid renewable resources for EV charging stations [14].

A large number of battery-operated EVs are currently operational in Bangladesh, with no charging policy and insufficient charging stations, similar to the scenario in other developing countries. However, Bangladesh presents considerable potential for the application of renewable resources such as solar and biogas energy, which can be utilized for power generation for EVCSs by using an efficient charging management scheme [15]. Although solar energy is a crucial resource for electricity generation, it can be harvested effectively only for a few hours a day [16]. Conversely, biogas resources can generate electricity during the hours when solar energy is absent [17]. Hence, hybridizing these resources can help realize reliable and efficient power generation. Research on hybrid power generation using renewable resources has demonstrated its cost-effectiveness, energy efficiency, and environmental sustainability [18], [19]. However, the lack of an energy management system significantly hinders hybrid power generation for EV charging.

Energy management schemes enable maximum utilization of renewable energy with the lowest possible charging cost. Fuzzy logic-based algorithms are typically robust since they are not vulnerable to changes in the environment or incorrect commands. Additionally, fuzzy logic models are more suitable for intelligent systems owing to their tendency to model human speech patterns and decision-making capabilities. Fuzzy logic-based energy management schemes are generally used in EV charging station management due to their simplicity, flexibility in defining rules, and capability to model non-linear functions with a wide range of operating conditions [20], [21]. Several studies report optimal charging/discharging scheduling provides EV user satisfaction with a dynamic pricing scheme considering solar and hybrid PV-Wind [22], [23], [24]. The potential of hybrid renewables such as solar and biogas need to analyze for obtaining real-time charging rate for EV customers and reducing GHG emissions. The existing literature also considers V2G/V2V/V2H technology to transfer energy during peak hours [25], [26]. The use of these technologies benefits EV customers and strengthens the utility grid.

The literature survey of an energy management algorithm for EVCSs based on renewable resources can be divided into two parts. Table 1 describes the conventional energy management/optimization approach using various methods, and Table 2 illustrates the fuzzy logic-based energy management/optimization approach.

The fuzzy logic-based algorithm has gained considerable interest in engineering applications due to its features such as decision-making, pattern recognition, identification, optimization, and control [41], [42]. In most cases, the algorithm's efficiency depends on the input data. The algorithm can be designed based on historical input and expert knowledge; therefore, data on different EVs and the uncertainties of renewable resources are not required. Table 2 summarizes the existing literature on the fuzzy logic-based algorithm in EVCS with their considered parameters, outcomes, and knowledge gaps.

In developing countries, the EV charging stations are insufficient, leading to charging from residential connections, which presents considerable system loss and decreased profitability index [3], [5], [15]. Also, power quality problems in the distribution network attributed to uncoordinated and inefficient EV charging schemes [8], [9]. Consideration of

TABLE 1. Literature related to the energy management system using various optimization methods.

Ref., year	Method	Contributions	Future Scopes
[27] 2020	Adaptive real-time dynamic programming	It reduces EV charging costs by up to 55% and 29% in summer and winter, respectively, by considering dynamic tariff, actual PV data, and vehicle parking behavior.	Only performed optimization for solar PV-based EVCS and neglected the departure time of EVs.
[28] 2021	Multi-objective particle swarm optimization	Proposed a flexible scheduling framework of PV-powered EVCS based on daily usage, including EV demand and the remaining state of charge of EV batteries.	Only analyzed daily scheduling operation and requires further analysis for a longer duration.
[29] 2020	HOMER techno-economic issues	Presents a grid-connected PV-battery system that reduces the EV charging cost and emission pollution.	Huge infiltration of renewables and EV charging patterns has not been considered.
[30] 2020	Mixed integer linear programming	The proposed model can reduce up to 78.3% of EV charging costs compared to the existing system by considering traffic route selection.	Further research is required on EV charging behavior and the integration of renewables.
[31] 2020	Parameter adaptive differential evolution algorithm	Established coordinated scheduling of EV charging using a wind power system that increased wind power absorption and reduced the charging cost and GHG emission.	It only considers wind power systems and does not consider hybrid renewable energy resources.
[32] 2020	EV charging scheduling using Bayesian network	Demonstrated that solar PV-based EVCS minimizes charging costs by considering EV charging demand and solar output generation.	The charging period/duration and existing tariff have not been considered.
[33] 2021	NSGA-II-based method and Monte-Carlo method	It presented an optimization approach to lower charging costs than existing tariffs considering load demand, energy cost, and state of charge of an EV battery.	It integrates wind energy for EVCS, and hybrid renewables may consider for boosting utility grid strength.
[34] 2019	Dynamic programming and stochastic analysis	Proposed a novel energy management strategy to reduce charging costs using multi-source EVCS by considering DERs, stationary ESS, and V2G.	The EV charging behavior, such as charging duration and time of charging, is not considered.
[35] 2020	Evolutionary particle swarm optimization	Reported a correlation between energy cost and control metrics by considering dynamic prices, EV charger type, and distribution network restrictions.	EV charging period/duration and renewable energy integration have not been considered.
[36] 2019	Approximate dynamic programming (ADP) and the evolution algorithm (EA.)	This study presented a cost reduction of over 50% compared to conventional charging by considering dynamic tariffs and charging demand.	Integration of renewables, time of charging, and duration have not been considered.
[37] 2020	Monte-Carlo simulation	Proposed a technique to determine an optimal number of charging points in EVCS and reduce the charging and waiting times.	It did not consider renewable energy integration and EV charging cost.
[38] 2019	Mixed integer non-linear programming	Improved the voltage profile and optimized power loss of the distribution grid by considering DERs and the number of EVs.	Only several EVs are considered, while the period and duration of charging are ignored.
[39] 2019	Mixed integer linear programming	It reduced EV charging costs by integrating PV systems.	EV charging patterns and other renewables have not been considered.
[40] 2018	Teaching-Learning Based Optimization	Proposed a PV-wind-battery hybrid system that minimizes energy costs considering EV power demand.	EV charging behavior, and charging period, i.e., peak/off-peak hour, have not been considered.

uncertainties present in renewable energy integration for EV charging for improving reliability issues need to analyse [23]. Hybrid solar and biogas-based power generation is more effective compared to the standalone PV systems for EV charging [18], [23]. Hence, an energy management scheme is required for EV charging to maximize renewable utilization. Research has been carried out on EVCS optimization, where the location, EV power demand, charging priority, and charging duration is considered [43], [47], [50]. As the EVs arrive at charging stations mostly during peak hours, EVCS optimization considering the charging period (peak/off-peak hour), power generation from renewables, EV power demand, and real-time charging cost needs further research. Fixed charging prices for EV users increase congestion in the charging stations and hampers power quality by increasing load

TABLE 2. Summary of fuzzy logic-based EVCS optimization approaches.

Ref., Year	Considered EV parameter	Contribution	Future Scopes
[43] 2020	EV battery state of charge, parking duration, and power availability	Proposed a fuzzy logic-based charging scheme for optimal power distribution to the EVs, reducing stress on the power grid.	This energy management scheme has not considered charging cost, speed, availability, and user satisfaction.
[44] 2019	EV waiting time	Fuzzy logic-based charging scheduling balances the charging request rate and reduces congestion in a charging station.	Other performance factors, i.e., charging cost, availability, speed, and renewable integration must be considered.
[45] 2019	Charging convenience, charging period, and cost	Fuzzy logic-based optimization is proposed considering user satisfaction, charging time, and cost.	Real-time charging costs and grid stress are not reflected.
[46] 2019	EV demand, time of use	Reduces charging costs, satisfies EV demand, and avoids overloading by considering the time of use, critical peak price, and real-time pricing.	EV waiting time and integration of renewables are not considered.
[47] 2019	EV battery SOC, arrival, and departure time, charging cost	It presents a charging priority identification method using peak power demand and charging cost.	Power availability, integration of renewables, and EV waiting time can be considered.
[48] 2018	Battery SOC, grid voltage, the charging period	Proposed a fuzzy logic-based charging approach considering charging time, battery SOC, and grid voltage.	Charging cost, availability of charging slots, and speed must be considered for optimization.
[49] 2018	Initial battery SOC, solar irradiance, and number of EVs	Presented fuzzy control-based EVCS by considering initial SOC, number of EVs, and solar irradiance.	EV waiting time and real-time price are not considered.
[50] 2017	EV power demand	It proposes a fuzzy optimization model to maximize the parking lot profit by satisfying EV owner requirements.	Renewable energy-based charging scenarios can be considered.
[51] 2017	Charging reservation time, electricity price	Demonstrated an optimization scheme based on charging reservation time, derivation of charging reservation time, and electricity cost.	The charging period (i.e., peak or off-peak hour) and integration of renewables can be considered.

demand [27], [38]. Therefore, a real-time charging cost is needed for EV charging that benefits various stakeholders, i.e., distribution network operators, charging station owners, and EV users. In addition, the techno-economic and environmental analysis for energy management algorithms is absent in the existing literature [40], [46]. The contributions for this research are as follows-

1. Overview of the negative impacts of fossil fuel consumption on the environment and the need for alternative renewable resources.
2. Highlighting the limitations and challenges of EV charging in developing countries, and the potential for renewable resources such as solar and biogas energy in Bangladesh
3. Review of existing literature on energy management algorithms for EV charging, with a focus on fuzzy logic-based algorithms.
4. Proposal for a fuzzy-logic based energy management scheme considering hybrid renewables for EV charging.
5. Techno-economic and environmental analysis of proposed energy management algorithm for EV charging

The rest of the paper is organized as follows. Section II describes the current state of the EVCS and the potential of renewable energy sources in Bangladesh. Then, section III presents the conceptual design and cost estimation of the proposed hybrid EVCS. Next, section IV demonstrates a fuzzy logic-based optimization algorithm for EV charging which utilizes solar and biogas resources. Section V presents the results and discussion of the proposed EVCS, which includes a case study performed on the usage on weekdays and weekends. It also explains the GHG emission from different renewable energy sources. Lastly, Section VI presents the conclusion and future research implications.

II. CURRENT STATUS OF ELECTRIC VEHICLES AND RENEWABLE POTENTIAL IN BANGLADESH

A recent study reported that more than one million EVs are currently running in Bangladesh, including battery electric vehicles (BEVs) such as auto-rickshaws, easy bikes, and minshuku [52]. Each EV contains four or five 12 V batteries with electric charges ranging from 100 to 160 Ah. The batteries in these EVs are charged using a switch mode power supply (SMPS)-based charger from a 220 V AC supply. Since the EVs primarily operate in the daytime, they are charged at charging stations in an uncoordinated manner at night, creating hazardous conditions. Despite the rapid implementation of EVs in Bangladesh, the Bangladesh Road Transport Authority (BRTA) does not have a licensing policy [53]. The Bangladesh Electricity Regulatory Commission (BERC) introduced a new charging tariff for EVs. The users must pay 0.0906 USD per kWh for charging and 0.4705 USD per kW per month as a demand charge. However, it is crucial to introduce licensing policies and charging guidelines due to the massive diffusion of EVs in Bangladesh.

EV users pay between 35.30 USD to 52.95 USD to charge a single EV at private charging stations. Several public charging stations based on solar energy have been established in

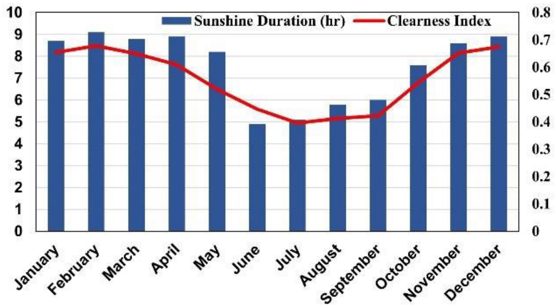

FIGURE 1. Month-wise solar radiation profile (Sunshine duration and Clearness index) in Bangladesh.

various parts of the country. However, this system cannot support continuous EV charging due to the limited effective charging period. Conversely, biogas resources such as municipal solid waste and animal waste present considerable potential for generating heat and electrical power and can help improve waste management. Consequently, research should focus on hybridizing renewable resources such as solar and biogas energy as practical solutions for charging EVs.

A. RENEWABLE SOURCES IN BANGLADESH: SOLAR BIOGAS

The electricity generation sector in Bangladesh is expanding rapidly, and the government is trying to develop a cost-effective, energy-efficient, and environment-friendly structure using renewable resources such as solar, biogas, and wind energy. The average insolation in Bangladesh is approximately 5 kWh/m^2/day, and the effective duration for solar Irradiation is 4-5 hours a day [54]. This scenario indicates that Bangladesh has a good prospect for solar power generation. The installed capacity of renewable energy-based power generation is 722.60 MW. Consequently, 4.5 million solar home systems have already been installed, and more than 65,000 are installed yearly [55]. Fig. 1 presents the solar irradiation profile for different regions of Bangladesh [56].

Furthermore, the vast availability of biogas resources such as municipal solid waste, animal waste, and other biodegradable wastes is favorable for electricity and heat generation. The average waste generation per person in Bangladesh is 0.5 kg, and the country's large population presents a considerable potential for generating electricity from this sector. The government is also developing a 1 MW biogas plant in Keranigonj, Dhaka. The Infrastructure Development Corporation Limited (IDCOL) is responsible for installing off-grid biogas plants in the country. However, solar biogas-based hybrid power generation stations, which can increase the efficiency of energy generation, have not yet been established in Bangladesh. Table 3 presents the prospects of renewable energy in Bangladesh.

III. DESIGN OF PROPOSED HYBRID RENEWABLE ENERGY-BASED EVCS

This section describes the proposed EVCS and the estimated cost for the charging station with the help of a conceptual block diagram. The proposed charging station contains a solar and biogas-based electricity generation system.

TABLE 3. Renewable energy prospects in Bangladesh [55].

Renewable source	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	346.58	142.1	488.67
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas	0.63	0	0.63
Biomass	0.4	0	0.4

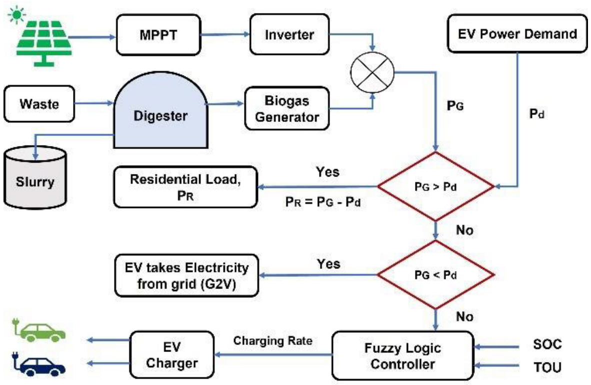

FIGURE 2. Conceptual block diagram of the proposed EVCS.

A. CONCEPTUAL BLOCK DIAGRAM OF THE PROPOSED EVCS

Fig. 2 presents a graphical representation of the proposed 20-kW EVCS, where the solar and biomass/biogas resources contribute equally (10 kW each) to the output hybrid power. The output power generated by the proposed EVCS is expressed as follows:

$$P_{Gen} = f(s, w) \tag{1}$$

where 's' and 'w' denote the solar Irradiation and waste inputs, respectively.

The average duration of sunlight is typically eight hours, from 8:00 AM to 4:00 PM. Solar energy cannot be generated on rainy and foggy days. In such cases, biogas resources are used to produce electricity in the absence of solar energy. The waste material is first fed into the digester, which generates the biogas through fermentation. The biogas is then fed to the generator input to produce electricity.

Additionally, the biogas system provides slurry, which is used as fertilizer and fish feed. When the EV demand exceeds the generated power of the charging station, excess power is obtained from the utility grid. In this case, a fuzzy logic controller is employed to optimize the charging cost for different EVs at different periods. The output-generated power availability, power demand of the EVs, charging period, and current charging rate are considered input variables. The

TABLE 4. Cost of hybrid renewable energy-based EVCS.

Items and specifications	Capital cost (USD)	Replacement cost (USD)	O & M cost/year (USD)	Lifetime (years)
PV (10 kW) (37 × 275 W)	10000	5000	10	25
Biogas generator (10 kW)	2000	1000	50	5
Digester (2 × 4.8 m^3, 1 × 3.2 m^3)	5000	2800	1100	5
Bidirectional converter (10 kW)	2000	1000	2	5
Charging assemblies (12V, 100 Ah- 5 Pcs)	200	100	50	5

charging cost and renewable utilization are regarded as the output variables.

B. COST ESTIMATION OF THE PROPOSED EVCS

The total cost of the proposed charging station comprises the capital cost, replacement cost, and O & M cost of the hybrid renewable energy-based charging station. This charging station primarily requires PV systems (10 kW: 37 modules, with 275 W each), a biogas generator (10 kW), three digesters (4.8 m^3, 4.8 m^3, and 3.2 m^3), a bidirectional converter (10 kW), batteries, and charging assemblies. The size and rating of the solar panel and biogas digesters are selected based on their availability in the market [18]. Table 4 presents the cost and benefits of the proposed charging station.

IV. FUZZY LOGIC-BASED ENERGY MANAGEMENT SCHEME

This section explains the energy management system and fuzzy logic-based optimization model for EVCS incorporating hybrid renewable resources. The optimization algorithm considers the maximization or minimization of one or more objective functions.

A. ENERGY MANAGEMENT SYSTEM OF EVCS

The energy management algorithm has two objectives: minimizing the charging rate and maximum utilization of renewable resources. The objective functions can be expressed as follows:

$$Min\left(C_{Charging}\right) \text{ and } Max\left(Ren_{Utilization}\right)$$

This objective function works under the following constraints:

$$SOC_{max} \geq SOC_i \geq SOC_{min} \tag{2}$$

$$T_D = \frac{(SOC_{max} - SOC_{min}) \times C_{Batt}}{\eta \times L_{ch}}; \quad 0 \leq T_D \leq 10 \; and \; L_{Ch} \in (1, 2) \tag{3}$$

$$P_{Gen} \geq P_{EVCS} \tag{4}$$

T_D represents the charging duration measured in hours, which varies between 0 to 10 hours. L_{Ch} denotes the charging level. In this study, only Level 1 (3.7 kW) and Level 2 (6.6 kW) are considered since Level 3 charging (≥50 kW) is not available in the analyzed areas. The generated power, P_{Gen}, depends on the availability of renewable resources. It is also affected by the variation of the electricity prices in the proposed EVCS.

The power limit is generally more useful when there is a diesel generator to meet extra power demand. In this paper, the SOC limits are used to avoid EV battery degradation. Also, battery is mainly responsible to meet high/low ramp rate that mostly suits with SOC limits for more feasible EV charging. The power demand of the EV depends on the SOC and battery capacity. In the proposed model, the minimum SOC is considered 20%, and the maximum SOC is 80%. The battery capacity for the considered EVs varies from 8 kWh to 10 kWh. The proposed hybrid renewable generation enables the daily recharging of 15–20 EVs based on the initial SOCs.

The self-generated power of the EVCS must be greater than or equal to the power demand of the EVCS. In such a case, renewable energy utilization becomes maximum. The charging duration, T_D is the time required to recharge the batteries. The charging duration of the EV is expressed as follows:

$$T_D = T_{stop} - T_{start} - T_w \tag{5}$$

where T_{start} denotes the charge starting time, T_{stop} denotes the departure time, and T_w indicates the waiting time. The charging period lies between T_{start} and the time of charging disconnection.

The charging period, T_C, is divided into peak and off-peak hours. The overall real-time charging cost is the function of the four input parameters: power availability, EV power demand, charging period, and existing tariff. It can be expressed as follows.

$$T_C = \begin{cases} PeakHour\ (5PM - 11PM) \\ Off - PeakHour\ (11PM - 5PM) \end{cases} \tag{6}$$

The real-time charging cost for the EVs, f_c, depends on the current charging cost, r(t), SOC, battery capacity (C_{Batt}), and duration of charging (T_D). EV arrives with low SOC increases power demand and cumulatively increases the overall power demand of the EVCS. The charging cost varies for different periods (peak/off-peak hours), which is fixed for the off-peak and peak hours in the area considered in the case study. f_c is obtained from the definite integral within the interval from T_{start} and T_{stop}, as shown below.

$$f_c = \int_{T_{start}}^{T_{stop}} \frac{(SOC_{max} - SOC_i) \times C_{Batt}}{T_D} \times r(t)\, dt \tag{7}$$

Annual cash in-flow can be calculated according to the conventional energy price per kWh, C_{kWh} multiplied by the total expected generation, P_{Gen}, from the EVCS. The payback

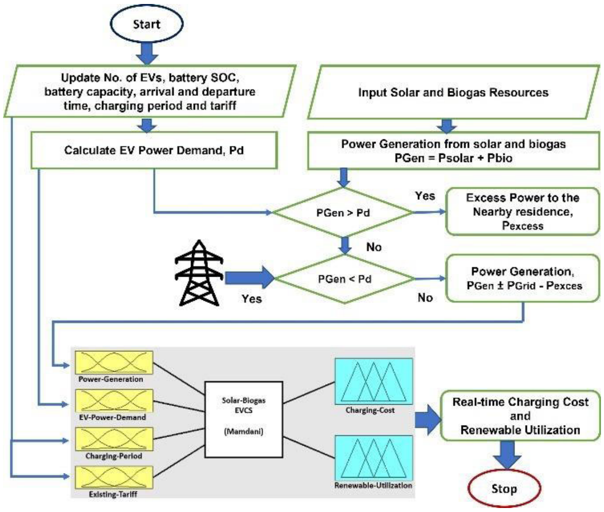

FIGURE 3. Proposed energy management system for EVCS.

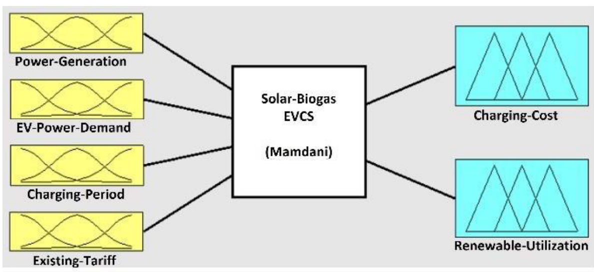

FIGURE 4. Fuzzy (Mamdani) optimization model for EVCS.

period can be calculated using the following equation (8).

$$PBP = \frac{C_{cap} + C_{rep} + C_{o\&m}}{P_{Gen} \times C_{kWh} \times T} \tag{8}$$

C_{Cap} and C_{rep} indicates capital cost and replacement cost where $C_{o\&m}$ represents operation and maintenance cost. The project lifetime is depicted by 'T' which differs for solar and biogas projects, affecting payback period. The payback period must be less than the project lifetime to be a successful project.

B. FUZZY OPTIMIZATION MODEL

The Mamdani-type fuzzy inference model is used in the proposed EVCS to obtain an optimized charging rate with renewable integration under various input conditions. The centroid-based defuzzification technique is employed in this modeling approach. The output power availability, power demand of the EVs, charging period, and the existing tariff are considered the input parameters of the fuzzy model. The charging cost and renewable utilization are considered the output parameters. Fig. 4 shows the input and output variables of the fuzzy (Mamdani) optimization model.

C. INPUT AND OUTPUT VARIABLES

In this fuzzy inference system, triangular, trapezoidal, and Gaussian membership functions describe the different stages of the input and output variables. The power availability

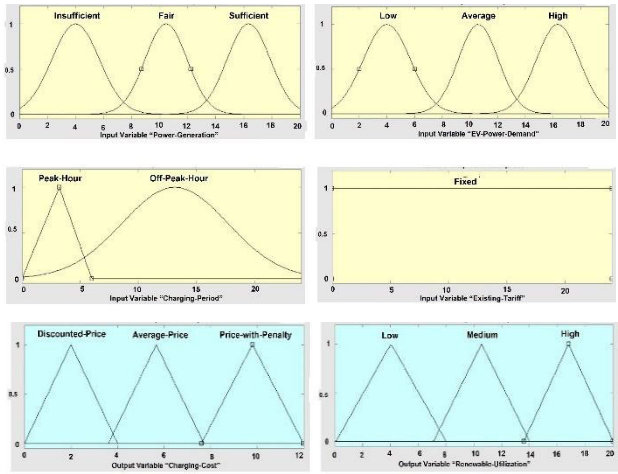

FIGURE 5. Input variable and output variables with membership functions.

of the EVCS depends on renewable input resources, i.e., solar and biogas energy sources. Power generation can be increased if the solar and biogas resources are sufficient. Conversely, when solar energy is absent, power generation is low. Therefore, the input parameter, "Power_Generation," is classified into three categories for the membership function (Insufficient, Fair, and Sufficient).

The power demand of an EV depends on the battery capacity and SOC. In this model, the membership functions of "EV-Power-Demand" are "Low," "Medium," and "High." The power demand varies since the EVs at the charging station have different battery capacities and SOC. For 0–8 kW, the membership function is defined as "Low," 8–14 kW is defined as "Average," and 14–20 kW is defined as "High." The EVs in Bangladesh are primarily recharged during the night; only a few are charged during the day. The easy bike and auto-rickshaw batteries generally require 8–10 hours for complete charging. However, the SOC of some of the EVs is above the minimum SOC; therefore, they need less time to recharge. Therefore, determining the charging duration is essential for calculating the power demand.

V. ANALYSIS OF RESULTS AND CASE STUDY

The proposed optimization system uses a fuzzy "if-then" rule-based strategy. The membership functions are defined based on the data of the existing Battery EVs in Bangladesh. Fig. 6 shows the fuzzy rule viewer where 18 rules are applied. The fuzzy rule viewer shows numerically how the output variables are changing with the changes in the input variable. Also, a fuzzy rule viewer can visualize how the rules are organized in this optimization approach. Output variables depend on power generated from hybrid resources, EV power demand, duration/period of charging, and existing tariff. The existing tariff is fixed for peak and off-peak hours. However, using this rule viewer, it is seen that the charging rate varies for different periods.

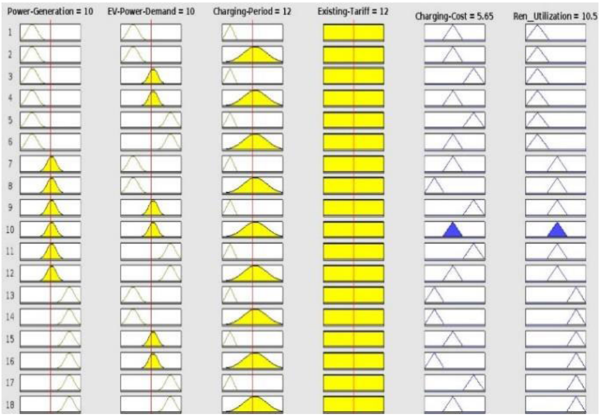

FIGURE 6. Fuzzy rule viewer.

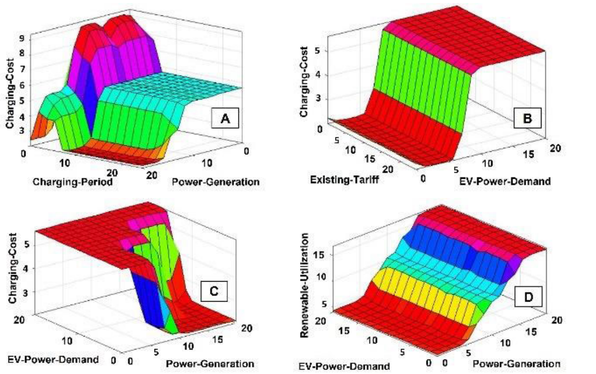

FIGURE 7. Surface view of output and input variables. (A) Surface view of Power-Generation, Charging-Period, and Charging-Cost, (B) Surface view of EV-Power-Demand, Existing-Tariff, and Charging-Cost, (C) Surface view of Power-Generation, EV-Power-Demand, and Charging-Cost, (D) Surface view of Power-Generation, EV-Power-Demand, and Renewable-Utilization.

A. DISCUSSION OF RESULTS

The proposed fuzzy-based optimization considers solar and biogas resources for minimizing EV charging costs. EV charging load depends on many uncertainties, i.e., arrival time, departure time, battery capacity, driving range, charging level, and state of charge of the EV battery. Conventional EVCS offers flat rate tariffs for EV customers. Hence, EV customers arrive at EVCS randomly, which creates power quality problems during peak hours. Besides, solar-based EVCS can provide power to the EVs during day time. Therefore, solar-biogas-based EVCS with dynamic charging rates inspire customers to charge their EVs at off-peak hours at a lower cost. Also, solar-biogas-based EVCS reduces dependencies on the utility grid by utilizing hybrid renewables and limits GHG emissions. Fig. 7 (A), (B), (C), and (D) show the 3-D surface view for the input and output variables of the fuzzy inference system.

From the 3-D surface view, it is seen that during peak hours, the charging rate is higher because, during that time, solar is absent, and only biogas resources are available to charge the EVs. If the power generation is low to meet the EV demand, then the power will come from the utility grid (grid to vehicle mode). During the off-peak hour and peak hours, when the EV load demand is lower than power generation, EVs can transfer energy to the grid or nearby residence (vehicle to grid or vehicle to residence mode). Solar and biogas can generate electricity during the daytime, offering lower charging costs. The renewable energy utilization will be maximum, and the corresponding charging cost will be minimum, although the highest number of EVs are connected during off-peak hours.

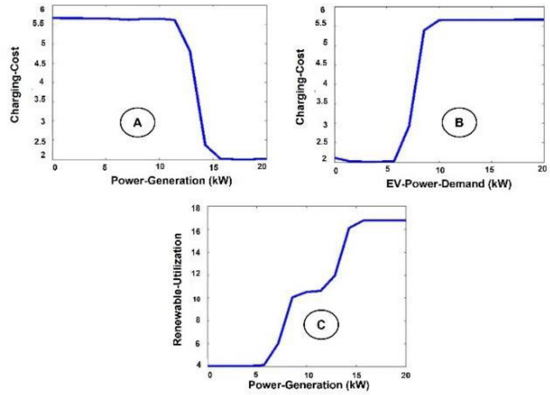

FIGURE 8. Variation of input and output variables. (A) Variation of Charging-Cost against Power-Generation (B) Variation of Charging-Cost against EV-Power-Demand (C) Variation of Renewable-Utilization against Power-Generation.

Fig. 8 (A), (B), and (C) show the variation of Charging-Cost and Renewable-Utilization with Power-Generation, EV-Power-Demand, and Charging-Period.

Fig. 8 (A) shows that the charging cost decreases with sufficient power availability and increases when the power availability is low. If the power generation by solar and biogas resources increases, the charging price tends to decrease. The increased power availability inspires EV owners to recharge their batteries at a lower cost.

Fig. 8 (B) explains the variation in the charging price with the EV power demand. The charging cost decreases with the EV power demand and increases with the EV power demand. In most cases, EV power demand increases during peak hours, affecting the distribution network's performance. Hence, while Ev power demand increased, the charging cost also increased in real-time pricing schemes. It inspires the EV customer to go for scheduled charging during the off-peak hour.

Fig. 8 (C) illustrates the variation in renewable utilization compared to power generation. Since the proposed EVCS employs solar and biogas resources for power generation and the power availability depends on these resources, insufficient power availability indicates that the solar and biogas resources are not working optimally. As the proposed EVCS mostly depends on renewable resources; hence increasing renewable integration leads to more power generation to support EV charging.

Therefore, power availability is higher when renewable resources are abundant, which reduces the corresponding

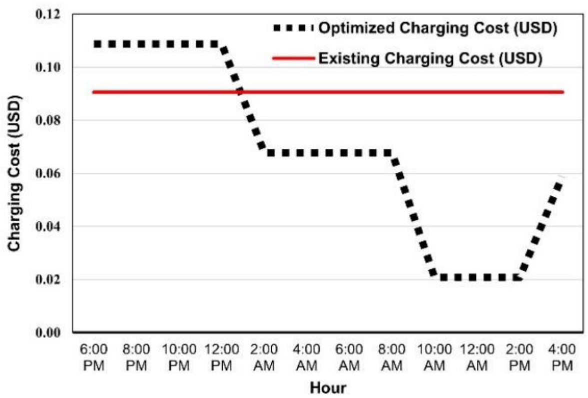

FIGURE 9. Fuzzy logic-based dynamic charging rate compared with existing flat rate tariff in Bangladesh.

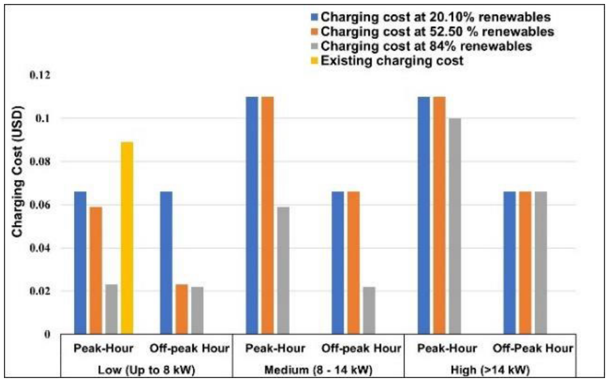

FIGURE 10. Comparison of charging costs at different renewable penetration scenarios with existing charging costs.

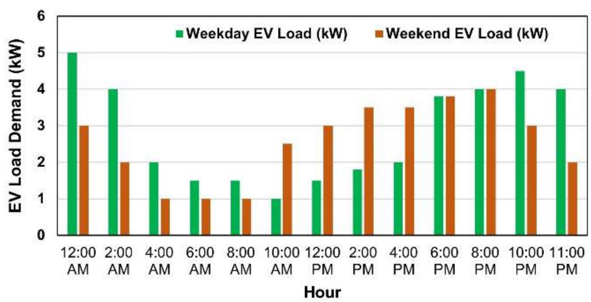

FIGURE 11. Daily EV load profile.

charging cost. In the proposed fuzzy logic-based EVCS, the charging rate for peak hours is more significant than the off-peak hours. EV users in Bangladesh must pay an average of 1.411 USD to 1.7647 USD to charge an EV battery in the conventional EVCS. According to the electricity tariff determined by the Bangladesh Energy Regulatory Commission, the battery charging rate is set to 0.0906 USD per kWh of electricity consumption. However, the optimization of the proposed EVCS based on hybrid renewable resources presents dynamic tariff rates for different charging times, durations, battery capacities, and availabilities of the power generated by the EVCS itself. The proposed method introduces an optimized charging cost, as shown in Fig. 9. The battery capacity for the considered EVs varies from 8 to 10 kWh. The 20 kW of power generated by the proposed EVCS enables 15–20 EVs to recharge the batteries daily based on the initial SOCs.

A conventional charging station has a maximum charging rate of 0.0906 USD per kWh, whereas the fuzzy logic-based EVCS presents a rate of 0.109 USD at peak hour conditions. During off-peak hours, the proposed EVCS requires 0.023 USD to 0.068 USD per kWh based on different needs. The minimum charging rate of 0.023 USD occurs from 10:00 AM to 2:00 PM, which reduces the charging costs by up to 74.67% compared to the existing flat rate tariff.

Fig. 10 compares the charging costs at different renewable energy penetration scenarios with the existing ones. This type of optimization motivates the EV owner to recharge the EV batteries during off-peak hours, which can further reduce the demand during the peak hour period. Additionally, solar energy is available during the daytime, and charging the batteries using solar energy resources will maximize renewable energy utilization and reduce the excess battery requirement for the EVCS.

The proposed algorithm promotes using hybrid renewable energy for EV charging stations. It helps to strengthen the distribution network by reducing EV load demand during peak hours. This algorithm inspires EV owners to recharge the batteries during an off-peak hour at a lower cost while renewable utilization is maximum. Besides, this energy management algorithm enhances the EV scheduling strategy to improve user satisfaction. Moreover, reducing GHG emissions compared to the conventional utility grid-based EVCS significantly fosters environmental sustainability.

B. EV CHARGING COSTS DURING WEEKENDS AND WEEKDAYS

In the case of weekends and weekdays, the EV load profile varies based on the demographic profile of the EV driver. Fig. 9 presents the weekend and weekday load profiles for a conventional grid-based EV charging station in Bangladesh. The Levelized cost of charging for the proposed EVCS is 0.1302 USD per kWh [18].

The proposed optimization approach is applied on both weekdays and weekends to observe the performance. On weekdays, the tendency of EV drivers to arrive at the EVCS increases in the evening and continues until the following day. On weekends, in most cases, the EV drivers start charging the EVs from 10 AM; this trend decreases from midnight. Since the charging occurs during an off-peak hour for most of the weekend when solar energy is available, the tariff for weekend charging is low. However, in the case of weekdays, most of the EVs arrive at the charging station during the peak hours when renewable generation is minimum, which results in a higher charging rate.

The simulation results indicate that the average charging cost for EVs is approximately 0.095 USD per kWh

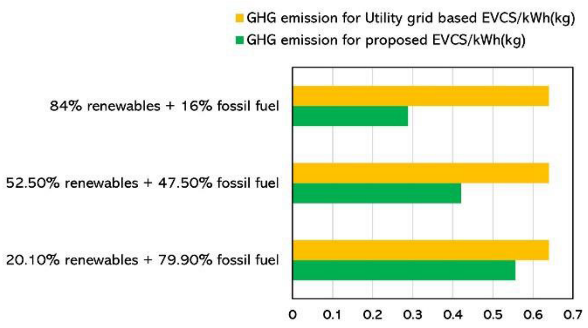

FIGURE 12. Comparison of GHG Emission from conventional utility-based EVCS and proposed EVCS.

on weekdays and 0.079 USD per kWh on weekends. The fuzzy optimization-based EVCS reduces the charging costs by 46.15% and 55.22% on weekdays and weekends, respectively, compared to the average cost. EV charging affects the distribution network since it consumes large amounts of energy. During peak load conditions, EV charging affects the distribution network, resulting in voltage fluctuations and power loss. Conversely, EV charging during off-peak hours can benefit the power system and the consumers. In Bangladesh, the off-peak period is between 11 PM and 5 PM, and peak hours are between 5 PM and 11 PM. Due to the lower power demand during the off-peak hour, the charging rate will be less than during the peak hour.

C. GHG EMISSION

In Bangladesh, almost all the power stations use fossil fuels such as coal, gas, and diesel, which are this sector's primary sources of GHG emissions. Previous studies have reported that Bangladesh's high per-kWh electricity consumption is responsible for approximately 0.64 kg of CO_2 production and some other greenhouse gases, which are in trace amounts [57], [58]. Besides, daily generated waste creates environmental pollution, and managing the vast waste is quite challenging. Hence, the effective utilization of these wastes for generating heat and electricity that reduces environmental pollution. A study concludes from an analysis of PV-biogas hybrid power stations using the HOMER Pro software that for one kWh of electricity generation, the GHG emission is about 0.222 kg which is one-third of the fossil-fueled power station [18]. Hence, using renewables such as solar and biogas combined reduces GHG emissions, further improving environmental parameters' quality.

Figure 12 compares the GHG emissions from the proposed EVCS and conventional grid-connected EVCS. It is seen that with the increase of renewable penetration, the power obtained from the utility grid to satisfy the excess electricity demand decreases, leading to a decrease in indirect GHG emissions. The maximum GHG emission reduction of up to 54.86% can be obtained using a mix of 84% renewables and 16% fossil fuel. Also, it depicts increasing renewable utilization decreases GHG emissions from the EVCS.

TABLE 5. Economic parameters from the proposed EVCS.

System	Annual energy generation (kWh)	Lifetime (years)	Annual cash in-flow (USD)	Payback period (years)
PV	15350	25	1880	10.1
Biogas	24820	5	3040	3.27

D. SOCIO-ECONOMIC IMPACTS

The proposed charging station would be profitable for EVCS owners and EV customers since the depreciation of the charging cost corresponds with the objective of maximization of renewable utilization. The use of renewable resources increases the cost-effectiveness of electricity generation. The EV owners benefit significantly due to the scheduled and economical charging at the proposed EVCS. The number of EVs is rapidly rising in Bangladesh, similar to other developing countries, which presents an excellent opportunity for reducing unemployment. Furthermore, this mode of transportation is cheaper than any different mode. Table 5 summarizes the economic benefits of the proposed charging station. The payback period is determined using equation (8) for solar PV, and biogas is calculated separately, having different lifetimes.

Solar resources are absent only on rainy/foggy days and at nighttime. In such cases, the biogas resources in the proposed EVCS effectively utilize waste material to generate electricity. Biogas resources for electricity generation produce less CO_2 than fossil-fuel power stations [18]. Effective management of generated waste to produce electricity can reduce GHG emissions. Also, digestate produced as a slurry can be used in agriculture. Hence, it helps to improve the quality of environmental parameters in two ways: generating electricity and managing waste. The proposed EVCS has a 10-kW solar system and a 10-kW biogas-based power generation system, which supply 15350 kWh and 24820 kWh of energy, respectively. Therefore, the hybrid charging station can be operated 24 hours a day. The total amount of power generated in a single day is 110 kWh. In Bangladesh, most battery-electric vehicles consume 8–10 kWh every day. The daily power generation of the EVCS enables the charging of 15–20 BEVs based on the battery SOC.

Additionally, the digestate produced from the biogas digester can be used as fertilizer and fish food. Based on all these socio-economic and environment-friendly features and the energy management scheme, it can be stated that the proposed hybrid renewable energy-based EVCS is profitable and sustainable and promotes a clean environment.

VI. CONCLUSION

The growing popularity of EVs opens new avenues for research on renewable integration. This study aimed to design and develop an optimization algorithm for an EVCS using solar and biogas/biomass resources. Additionally, the considerable potential presented by renewable resources for electricity generation in off-grid areas is explored in this study. The proposed approach is helpful for effectively utilizing the available renewable resources to reduce GHG emissions and the stress from the distribution grid due to EV charging.

The fuzzy optimization algorithm optimizes the charging cost based on the power availability, EV power demand, charging period, and existing tariff while the renewable utilization becomes maximum. It demonstrates that the hybrid renewable energy-based EVCS presents a lower energy cost, especially during off-peak hours, which can inspire EV owners to recharge the batteries during such a period. Also, it reduces power quality problems during peak hours due to lesser demand. Furthermore, it reduces the daily charging cost by 46.15% and 55.22% on weekdays and weekends, respectively, compared to the average cost. It demonstrated that CO_2 emission from the proposed EVCS is 54.86% lower than that of the conventional grid-based EVCS when 84% of the renewable resources are integrated with the EVCS. Accordingly, with shares of 52.50% and 20.10%, renewable resources reduce GHG emissions to 34.28% and 13.12%, respectively.

This study primarily focuses on applying solar and biogas resources in a hybrid mode for EV charging and developing an effective energy management system for the proposed EVCS. In the future, the experimental analysis will be performed to validate and observe the real-time performances. Furthermore, the environmental effect of implementing the proposed EV charging infrastructure throughout the country, which is of considerable research interest, will be analyzed in detail.

The optimization of the proposed hybrid renewable energy-based EVCS can be achieved using other algorithms, such as particle swarm optimization (PSO), the genetic algorithm (GA), and the GA-PSO algorithm, for better results. The performance comparison of these algorithms for EVCS optimization presents considerable research potential. The proposed optimization approach can be implemented to establish a sustainable charging infrastructure worldwide.

Lastly, a new scheme can be designed as a bidirectional energy transfer facility similar to a smart grid for the EVCS, known as the V2G (Vehicle to Grid) technology. During blackout and peak hour periods, the EVs can transfer energy to the utility grid through this scheme. This study contributes significantly to the sustainable development of power system networks and the transportation sector, and the proposed strategy presents various techno-economic and environmental benefits.

CONFLICT OF INTEREST

The authors declare that the research was conducted without any commercial or financial relationships construed as a potential conflict of interest.

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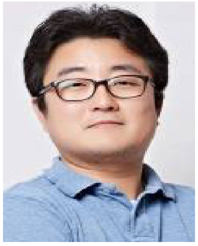

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