

Vehicle-to-Grid (V2G) Enabled Renewable-Powered Microgrids: A Sustainable Approach to Carbon Emission Reduction

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Abstract: The increasing use of electric vehicles (EVs) raises electricity demand and questions the environmental impacts of EV charging by electricity produced from fossil-fuel sources. Integrated renewable-based microgrids with vehicle to grid (V2G) enable coordinated renewable generation, EV charging and discharging, battery energy storage and grid exchange to minimize carbon emissions. This paper proposes an energy management framework for V2G-enabled renewable-powered microgrids by which the carbon emissions are minimized, while the utilization and operational efficiency of the system are maximized. The proposed system comprises photovoltaic (PV) generation, bidirectional EV charging, battery energy storage system (BESS) and grid-connected microgrid. An energy management policy is formulated to prioritize renewable utilization, schedule EV charging during high solar generation, utilize V2G discharging during high demand, and manage battery operations in accordance with operational constraints. The performance of the proposed framework is evaluated in terms of carbon emissions, renewable utilization, grid exchange, battery operations and operational costs. Comparative scenarios of conventional grid-connected charging, renewable-powered charging and V2G-enabled renewable microgrids are defined to quantify the contribution of each technology to the system performance. The proposed framework provides a systematic basis for assessing the technical and environmental benefits of coordinated V2G operations and their contribution to sustainable and low-carbon electricity systems.

Keywords: Vehicle-to-Grid, Renewable Energy, Electric Vehicles, Carbon Emission Reduction, Energy Management, Sustainable Development, and Smart Grid.

I. INTRODUCTION

The proliferation of electric vehicles (EVs) has become an effective approach to reducing greenhouse gas emissions. In addition, it reduces the reliance on fossil-based energy sources as well as increases the need for electricity for EV charging. Grid-tied EV charging may cause voltage fluctuations, congestions, and increased carbon emissions, especially if the electricity is generated using conventional methods. Sustainable and efficient EV charging methods need to be developed to reduce the adverse impacts associated with conventional approaches.

Microgrids equipped with renewable energy sources such as solar photovoltaics and batteries can be utilized in developing sustainable EV charging solutions. The microgrids can operate in grid-connected or stand-alone modes and offer flexibility to the system. In addition, the use of renewable energy sources reduces the negative impact of EV charging on the environment. Nonetheless, the use of microgrids with integrated renewable energy sources requires an advanced energy management system due to the intermittent nature of renewable energy sources and the variable electricity demand from EVs.

The vehicle-to-grid (V2G) technology provides flexibility and facilitates demand-response in renewable-powered microgrids with EVs. Unlike the conventional one-way energy flow in EVs, V2G enables EVs to store electricity in their batteries and sell the electricity back to the grid. It supports peak shaving, renewable energy utilization, and grid stability while reducing electricity consumption from the grid. However, the integration of V2G technology requires considering several factors, including the EV's availability for electricity storage, battery's state of charge, charging stations, and electricity prices. In addition, the degradation cost of EV batteries should also be considered.

The coordinated control of solar photovoltaic generation, EVs charging and discharging, battery energy storage, and grid power flow in a V2G-enabled renewable-powered microgrid is not a trivial task. A proper control strategy should be

developed to manage the power balance in the microgrid while considering the EVs' charging needs, battery's state of charge, and grid electricity demand. In addition, carbon emission reduction, renewable energy utilization, and cost minimization should be considered in the development of a control strategy for the V2G-enabled renewable-powered microgrid.

The present research aimed to develop a V2G-enabled renewable-powered microgrid for sustainable EV charging and carbon emission reduction. The research will adopt a system consisting of a photovoltaic power generation system, battery energy storage, bidirectional EV charging system, and grid connection under an energy management system. A coordinated energy management strategy will be developed to prioritize the use of renewable energy sources, manage the electricity stored in the battery, and control the power flow from the grid to the EV charging station. The developed system can be simulated using MATLAB/Simulink to evaluate the performance of a V2G-enabled renewable-powered microgrid in supporting sustainable EV charging. The simulation experiments will adopt three EV charging scenarios, namely: grid-connected EV charging, renewable-powered EV charging with batteries, and V2G-enabled renewable-powered EV charging.

The present research aimed to assess the potential of the V2G-enabled renewable-powered microgrid in promoting sustainable EV charging and reducing the negative impacts of EVs on the environment. The impact of the V2G-enabled renewable-powered microgrid on the grid electricity consumption, renewable energy utilization, carbon emission, battery's state of charge, and operating cost will be evaluated. The operational performance of the V2G-enabled microgrid will be compared to the conventional EV charging approaches to establish their potential and limitations in promoting sustainable development.

II. LITERATURE REVIEW

A. Renewable Energy-Powered Microgrids

Renewable energy microgrids have attracted much research interest, due to their ability to combine distributed energy resources and controllable loads. Solar PV and wind power, which are commonly thought to decrease the reliance on traditional electricity generation, have unpredictable generation patterns. Thus, flexible resources and appropriate energy management strategies are required.

The energy management of microgrids typically deals with generation-demand balancing, subject to the operational constraints. Grid-connected microgrids can import energy during renewable shortages and export the stored energy when needed. The use of energy storage can enhance the flexibility by shifting the energy between periods of low and high generation.

For EV charging purposes, the renewable-powered microgrids can enable the coordinated charging to balance the demand and generation. Nevertheless, the performance of such systems is limited by the amount of renewable generation, the size of energy storage, the EV charging needs, the power conversion losses, and the electricity pricing [1].

B. Vehicle-to-Grid Technology

V2G technology allows for the bidirectional flow of electricity between EV batteries and the grid. In the standard unidirectional charging process, electricity flows from the grid or microgrid to the EV. In the V2G charging process, a compatible bidirectional charger allows electricity to flow from the EV battery to the microgrid [2].

The V2G offers various benefits such as:

- Peak shaving.
- Balancing of renewables.
- Load shifting and demand response.
- Short-term storage,
- Grid support, and power balancing.

However, the V2G process has some disadvantages, such as the increased risk of battery degradation due to the cycling of electricity. The availability of cars for V2G is also limited by user travel plans and willingness. Lastly, power conversion and charger costs play a significant role in determining the economic viability of V2G.

C. Renewable Energy and Carbon Emission Reduction

The carbon emission benefits of using renewable powered EV charging depend on the electricity generated by renewable sources. Solar PV can reduce the import of electricity from the grid when there is sufficient solar output. Combined with energy storage, renewable electricity can potentially satisfy EV charging demand outside solar generation hours [3].

V2G can provide additional flexibility by enabling discharging of EVs during periods of high demand or low-renewable generation. However, the carbon benefit of V2G technology depends on the source of the previously stored electricity in

the EV battery. Discharging electricity obtained from a carbon-intensive grid can have less environmental benefit than discharging energy obtained from a surplus of renewable electricity generation.

As such, carbon emission assessment should consider the source of the electricity, charging and discharging efficiency, and the emission factor of imported electricity. The analysis should also distinguish operational emissions from the lifecycle emissions of solar panels, batteries, and EV manufacturing [4].

D. Research Gaps

The following research gaps motivate the proposed framework.

TABLE 1 Research Gaps

Research area	Existing challenges	Proposed research direction
Renewable-powered EV charging	Intermittent renewable generation and variable EV demand	Coordinate PV generation with EV charging
V2G integration	Battery availability and charging constraints	Incorporate EV availability and minimum departure SOC
Battery energy management	Uncoordinated use of stationary and vehicle batteries	Coordinate BESS and EV battery operation
Carbon emission assessment	Carbon benefits depend on the energy source and conversion losses	Use energy-flow-based operational carbon accounting
Economic operation	Battery degradation and electricity tariffs affect costs	Include energy purchase and battery degradation costs
Performance validation	Different studies may use different baselines	Compare three clearly defined operating scenarios

The proposed study deals with these aspects by developing an integrated modelling framework that emphasizes the joint assessment of renewable energy use, bidirectional power exchange, and carbon emission abatement rather than individual factors. [5]

III. TECHNICAL DYNAMICS OF V2G SYSTEMS

The technical basis of vehicle-to-grid (V2G) systems is based on the bidirectional flow of energy between electric vehicles (EVs) and the grid [6]. This characteristic makes EVs distributed energy resources (DERs), that is, resources that provide power to the grid while fulfilling their main purpose (transportation). Most of the surveyed papers address the technical aspects of V2G systems with three main areas: renewable energy (RE) integration, grid stability, and battery performance.

The most common application for V2G systems is the integration of RE into the grid. The intermittency of RE production is one of the most common problems facing RE integration. One way to address this is to use EVs to store surplus electricity generated when the demand is low and the supply is high and then utilize it in cases when the supply-demand balance is negative [7]. Studies confirm that V2G applications in microgrids with integrated RE provide economic benefits to the owner of the microgrid.

Another technical characteristic of V2G systems is their potential to increase grid stability. V2G EVs can provide grid ancillary services, such as frequency regulation, voltage regulation, and peak shaving. In particular, V2G EVs are well-suited for frequency regulation, which involves the balancing of electricity supply and demand in real time. This study confirms that utilizing V2G systems for this purpose demonstrates excellent potential for improving grid stability. [8].

The technical characteristics of V2G systems also concern batteries. The main type of batteries that are used in EVs are lithium-ion batteries. Their energy density is among the highest currently available due to their high discharge voltage, and they also exhibit excellent cycle life. The drawback of using lithium-ion batteries in V2G applications is that they undergo significant degradation due to repeated discharging and charging. Specifically, research suggests that the capacity of the batteries depends on the depth of discharge, temperature, and charging protocol [9]. Thus, while some papers have suggested that the cost of degradation in lithium-ion batteries is acceptable, others have reported that it is an issue.

At the distribution level, V2G EVs can increase grid efficiency by relieving congestion in transmission networks and increasing voltage at certain nodes. The increased use of V2G EVs will also improve the power quality in the distribution network by using new communication protocols such as ISO 15118 [10].

The advantages of V2G systems are not without disadvantages. One of the problems facing the implementation of V2G systems is related to technological barriers, such as the necessity to develop standardized communication protocols and energy management systems, as well as address cybersecurity issues. Another issue is the infrastructure for V2G EVs, which requires the widespread adoption of V2G-ready EVs and appropriate supporting infrastructure [11].

IV. PROPOSED SYSTEM ARCHITECTURE

The proposed V2G-enabled renewable powered microgrid comprises five primary elements: a solar PV generation system, an EV fleet with bidirectional chargers, a stationary BESS, a grid connection, and a centralized EMS. The microgrid is designed to operate in grid-connected mode with the possibility of islanded operation if appropriate grid-forming equipment and protection are incorporated. The primary objective of the EMS is to coordinate power flows while satisfying the load demand, EV mobility requirements, and equipment constraints.

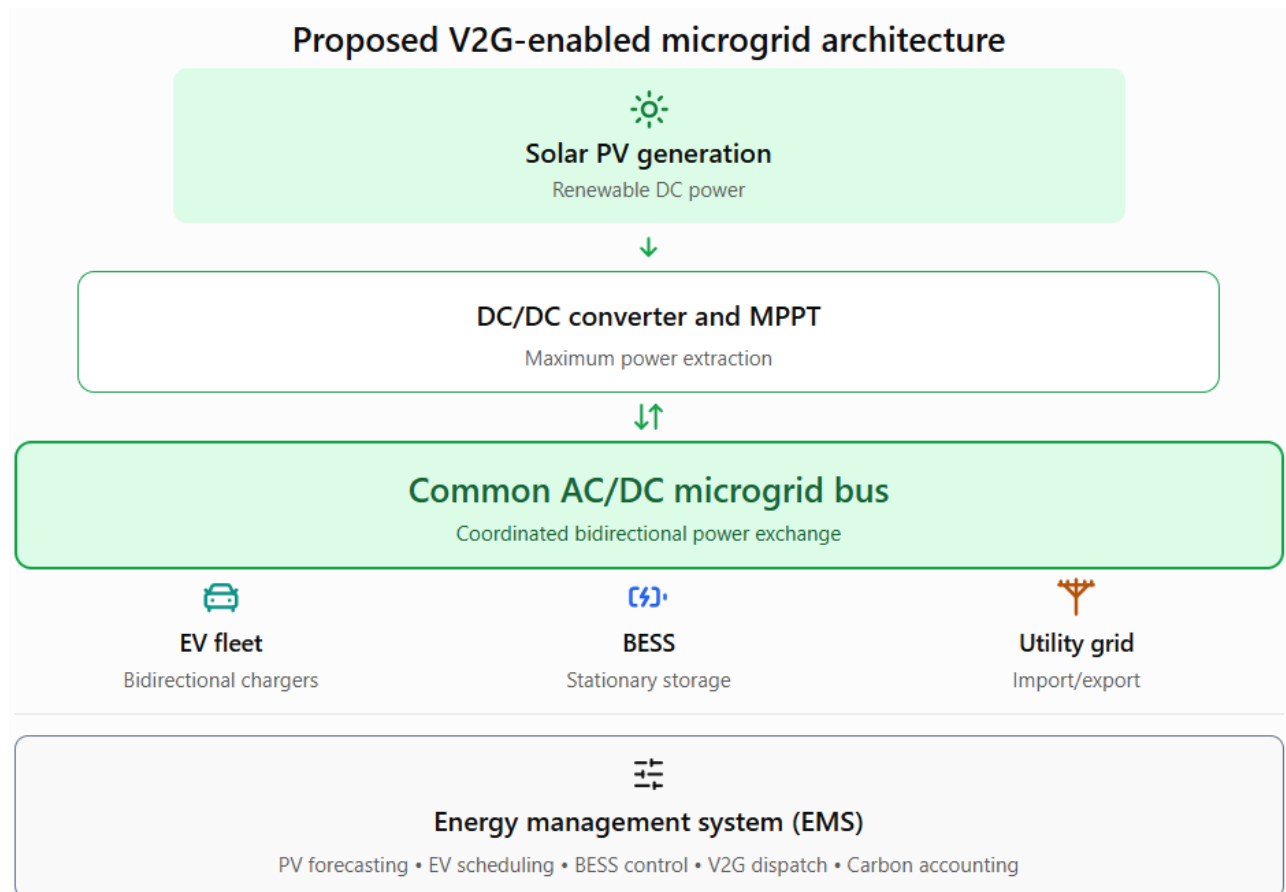


Figure 1 Conceptual architecture of the proposed V2G-enabled renewable-powered microgrid.

A. Solar Photovoltaic Generation System

The photovoltaic system was considered as the main renewable energy source in the proposed system. This system utilized solar radiation energy to generate direct current electricity by the photovoltaic modules. The independent variable for the PV system was the solar irradiance, as the energy output from the system depended on this value, along with the temperature of the modules, the nominal power of the PV modules, and the system's efficiency. The power was extracted from the PV panels by the MPPT controller.

The generated electricity was fed to the microgrid via the power converter. In cases of insufficient power demand, the produced electricity was stored in batteries or the connected electric vehicles (EVs). In cases of insufficient PV power, the energy could be taken from the battery storage or the electric grid via the EMS.

B. EV Fleet and Bidirectional Charging System

The EV fleet comprises vehicles that have bidirectional charging systems that can plug in to provide the necessary power. Each vehicle's battery size, SOC, charging and discharging power, connection availability, and desired SOC at which the vehicle leaves the charging station are given. When there is an excess of renewables, the EMS schedules EVs for charging based on their availability. The EMS can schedule V2G discharging of the vehicles if there is a high demand for power from the grid, and the vehicle has enough stored electricity and meets the SOC requirements at departure. The charging system should be able to safely handle the power conversion and ensure battery safety, and communication with the EMS. The V2G is only allowed to operate with compatible vehicles and chargers.

C. Battery Energy Storage System

A stationary BESS is used to balance the mismatch of the renewable generation and load. It is also used to store the electricity and to provide the energy at times of renewable energy shortage or high demand. The BESS is controlled based on the battery's state-of-charge (SOC), power limits, energy capacity, and charging and discharging efficiencies. The stationary battery can be combined with the EV battery, in which case, the EMS decides how to apportion the energy between the stationary and vehicle batteries. Overall, using two storage systems provides more flexibility; however, one should avoid using them together as much as possible since it increases costs without introducing significant advantages.

D. Utility Grid Connection

The proposed microgrid keeps its connection to the utility grid bidirectional. The grid electricity is imported when the locally produced renewable electricity and the stored energy are insufficient to meet the load. The surplus electricity can be exported to the grid if the grid import/export rules, contracts, and limitations allow. The grid import and export are controlled separately and limited according to the interconnection rating and power flow constraints. Thus, when operating in an island mode, the power exchange with the grid is turned off, and the microgrid has to balance its generation and load itself.

E. Energy Management System

The EMS (Energy Management System) is the central control component of the proposed architecture. It receives the information related to the PV generation, microgrid demand, EV connection status, battery SOC level, electricity tariffs and grid conditions.

The EMS has the following functions.

1. Estimates of renewable generation and electrical demand.
2. Prioritizes renewable energy for local loads and electric vehicle (EV) charging.
3. It controls the stationary battery charging and discharging.
4. Schedule EV charging and V2G discharging according to availability.
5. It maintains the grid power exchange within the permitted limits.
6. It monitors the SOC constraints and battery operating limits.
7. It calculates the energy costs and operational carbon emissions.

The proposed EMS first uses a rule-based approach because it can be implemented and verified in MATLAB without requiring extensive training.

V. MATHEMATICAL MODELLING AND ENERGY MANAGEMENT

A. Microgrid Power Balance

The instantaneous power balance is a primary operating constraint of the proposed microgrid. Assuming a common electrical bus, the active power balance can be expressed by the following equation

$$P_{PV} + P_G + P_{EV}^{dis} + P_B^{dis} = P_L + P_{EV}^{ch} + P_B^{ch} + P_{loss} \quad (1)$$

where:

- P_{PV} is the PV power supplied to the microgrid.
- P_G is the net power imported from the utility grid.
- P_{EV}^{dis} is the aggregate EV discharging power.
- P_B^{dis} is the BESS discharging power.
- P_L is the non-EV microgrid load.
- P_{EV}^{ch} is the aggregate EV charging power.
- P_B^{ch} is the BESS charging power.
- P_{loss} represents electrical conversion and distribution losses.

Positive P_G denotes grid import, while negative P_G denotes grid export.

For a discrete simulation with sampling interval Δt , the energy balance is obtained by integrating the power balance over each time interval. If a simplified energy-based model is used, converter and distribution losses must be accounted for separately.

B. Solar PV Power Modelling

The available PV power can be approximated using the following expression:

$$P_{PV}(t) = P_{rated} \frac{G(t)}{G_{STC}} [1 + \alpha(T_c(t) - T_{STC})] \quad (2)$$

where:

- P_{rated} is the rated PV power.
- $G(t)$ is the incident solar irradiance.
- G_{STC} is the reference irradiance at standard test conditions.
- α is the PV power temperature coefficient.
- $T_c(t)$ is the PV cell temperature.
- T_{STC} is the reference cell temperature.

The available PV power is constrained by

$$0 \leq P_{PV}(t) \leq P_{PV,available}(t). \quad (3)$$

The model can be extended using a single-diode PV equivalent circuit for detailed electrical simulation.

C. EV Battery SOC Modelling

The SOC of an EV battery is calculated by considering charging and discharging energy over each simulation interval.

$$SOC_i(t + 1) = SOC_i(t) + \frac{\eta_{ch,i} P_{ch,i}(t) \Delta t}{E_i} - \frac{P_{dis,i}(t) \Delta t}{\eta_{dis,i} E_i} \quad (4)$$

where:

- $SOC_i(t)$ is the SOC of EV i at time t .
- E_i is the usable battery energy capacity.
- $P_{ch,i}$ is the EV charging power.
- $P_{dis,i}$ is the EV discharging power.
- $\eta_{ch,i}$ and $\eta_{dis,i}$ are the charging and discharging efficiencies.
- Δt is the simulation interval in hours.

The EV SOC must satisfy

$$SOC_{i,min} \leq SOC_i(t) \leq SOC_{i,max}. \quad (5)$$

To satisfy the vehicle owner's mobility requirements,

$$SOC_i(t_{i,departure}) \geq SOC_{i,required}. \quad (6)$$

Charging and discharging power limits are represented as

$$0 \leq P_{ch,i}(t) \leq a_i(t) P_{ch,i}^{max} \quad (7)$$

$$0 \leq P_{dis,i}(t) \leq a_i(t) P_{dis,i}^{max} \quad (8)$$

where $a_i(t)$ is the EV availability indicator. It equals one when the vehicle is connected and zero otherwise. Simultaneous charging and discharging of an individual vehicle are prohibited.

D. Stationary Battery Modelling

The BESS SOC is modelled using an energy balance similar to that of EV batteries:

$$SOC_B(t+1) = SOC_B(t) + \frac{\eta_{B,ch} P_{B,ch}(t) \Delta t}{E_B} - \frac{P_{B,dis}(t) \Delta t}{\eta_{B,dis} E_B} \quad (9)$$

where E_B is the usable BESS capacity and $\eta_{B,ch}$ and $\eta_{B,dis}$ are the corresponding efficiencies.

The operating SOC limits are

$$SOC_{B,min} \leq SOC_B(t) \leq SOC_{B,max}. \quad (10)$$

The charging and discharging powers are constrained by

$$0 \leq P_{B,ch}(t) \leq P_{B,ch}^{max} \quad (11)$$

$$0 \leq P_{B,dis}(t) \leq P_{B,dis}^{max}. \quad (12)$$

The model must also prevent simultaneous BESS charging and discharging unless a more detailed converter model explicitly accounts for its operating characteristics.

E. Grid Power Exchange

The grid connection is modelled using the net power exchanged between the microgrid and the utility network:

$$-P_{G,exp}^{max} \leq P_G(t) \leq P_{G,imp}^{max}. \quad (13)$$

Here, $P_{G,imp}^{max}$ is the maximum permitted grid import and $P_{G,exp}^{max}$ is the maximum permitted grid export.

The grid power exchange is influenced by local generation, load demand, battery operation and EV power transfer. Grid imports are used to maintain power balance when local resources are insufficient.

F. Carbon Emission Modelling

Operational carbon emissions are calculated from grid electricity imports using a time-dependent grid emission factor.

$$C_{grid} = \sum_{t=1}^T P_{G,imp}(t) \Delta t EF(t) \quad (14)$$

where:

- C_{grid} are operational grid-related carbon emissions in kg CO₂e.
- $P_{G,imp}$ is imported grid power in kW.
- $EF(t)$ is the grid emission factor in kg CO₂e/kWh.
- T is the total number of simulation intervals.

If the emission factor is constant, Equation (14) can be simplified by using a single representative value. However, a time-varying factor is preferable when reliable hourly data are available.

The percentage reduction in operational carbon emissions relative to the baseline is calculated as

$$R_C = \frac{C_{base} - C_{proposed}}{C_{base}} \times 100. \quad (15)$$

This measure should be reported only when the baseline and proposed systems serve equivalent electrical and mobility demands over the same evaluation period.

G. Operating Cost Model

The operating cost consists of grid electricity purchases, export revenue, battery degradation costs and other applicable operating costs.

A simplified objective function is

$$J = \sum_{t=1}^T \Delta t [\lambda_{\text{imp}}(t) P_{G,\text{imp}}(t) - \lambda_{\text{exp}}(t) P_{G,\text{exp}}(t) + c_B(t) + c_{EV}(t)] \quad (16)$$

where λ_{imp} and λ_{exp} are the grid import and export tariffs, respectively. The terms c_B and c_{EV} represent battery degradation costs per unit time.

If the model excludes battery degradation costs, the resulting operating cost must be described as an energy-purchase cost rather than the total cost of V2G operation.

VI. MATLAB/SIMULINK SIMULATION FRAMEWORK

“Vehicle-to-Grid (V2G) Enabled Renewable-Powered Microgrids: A Sustainable Approach to Carbon Emission Reduction,” the following MATLAB code represents a microgrid with solar photovoltaic, battery energy storage system, five electric vehicles, a bidirectional charger, and a grid.

The model compares three operating scenarios:

1. Scenario 1: Conventional grid-connected EV charging.
2. Scenario 2: Renewable-powered EV charging with BESS.
3. Scenario 3: V2G-enabled renewable-powered microgrid.

The results are applied to assess the impact on the grid electricity consumption, renewable energy consumption, carbon emission, cost, and battery state of charge(SOC).

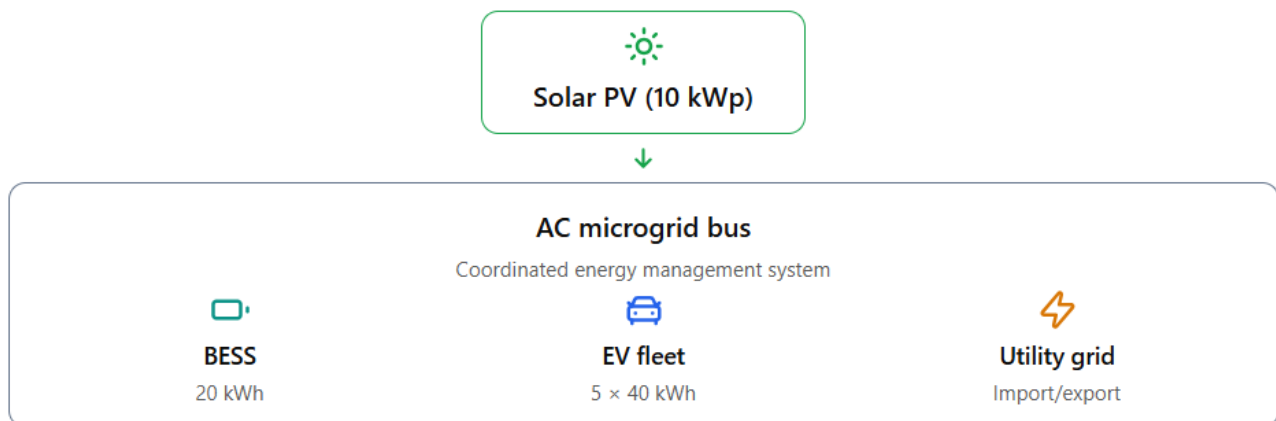


Figure 2 System Configuration

The model presented below is an illustrative example of an energy management simulation using a 24-hour time horizon and 1-hour time steps.

The proposed renewable-powered home EV charging system was modelled and analyzed using the MATLAB environment. The simulation was developed using the Simulink program which allows the representation of the energy generation and storage processes, as well as the load profile and EV charging control system. The model consists of a solar photovoltaic (PV) generation subsystem representing renewable power production, and battery energy storage (BESS) system model, and a residential load model representing the electricity demand profile.

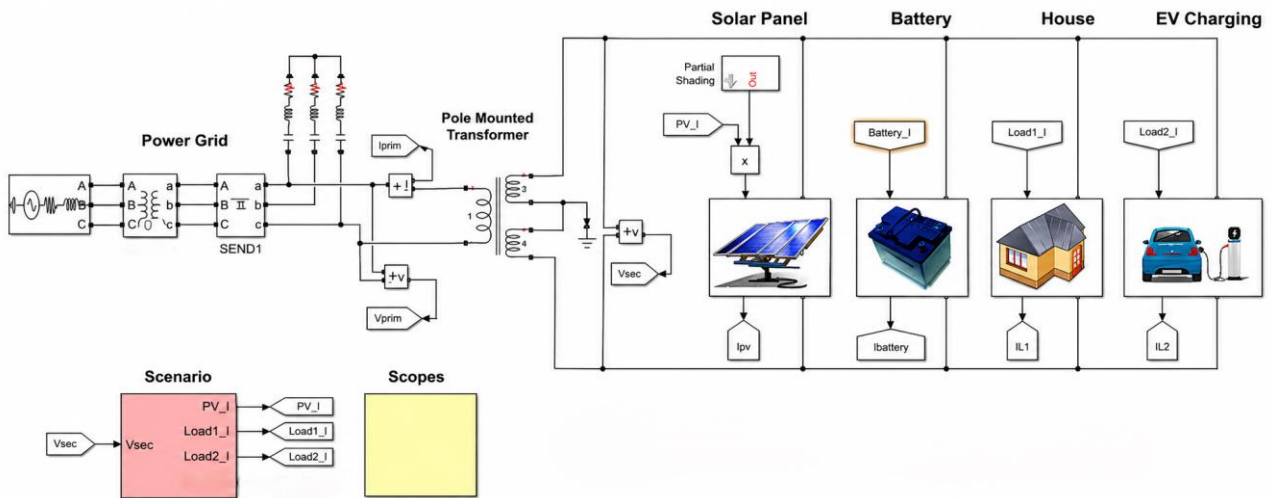


Figure 3 MATLAB/Simulink model of renewable-powered microgrid with V2G integration.

A. Simulation Parameters

Parameter	Value
Solar PV capacity	10 kWp
BESS capacity	20 kWh
Number of EVs	5
EV battery capacity	40 kWh each
Initial BESS SOC	50%
Initial EV SOC	60%
Minimum BESS SOC	20%
Maximum BESS SOC	90%
EV charging power	3.3 kW per EV
EV discharging power	3 kW per EV
Simulation duration	24 hours
Time interval	1 hour
Grid emission factor	0.70 kg CO ₂ /kWh

B. MATLAB Outputs

- Grid power exchange**

The grid-import graph compares the electricity required from the utility under the three operating scenarios.

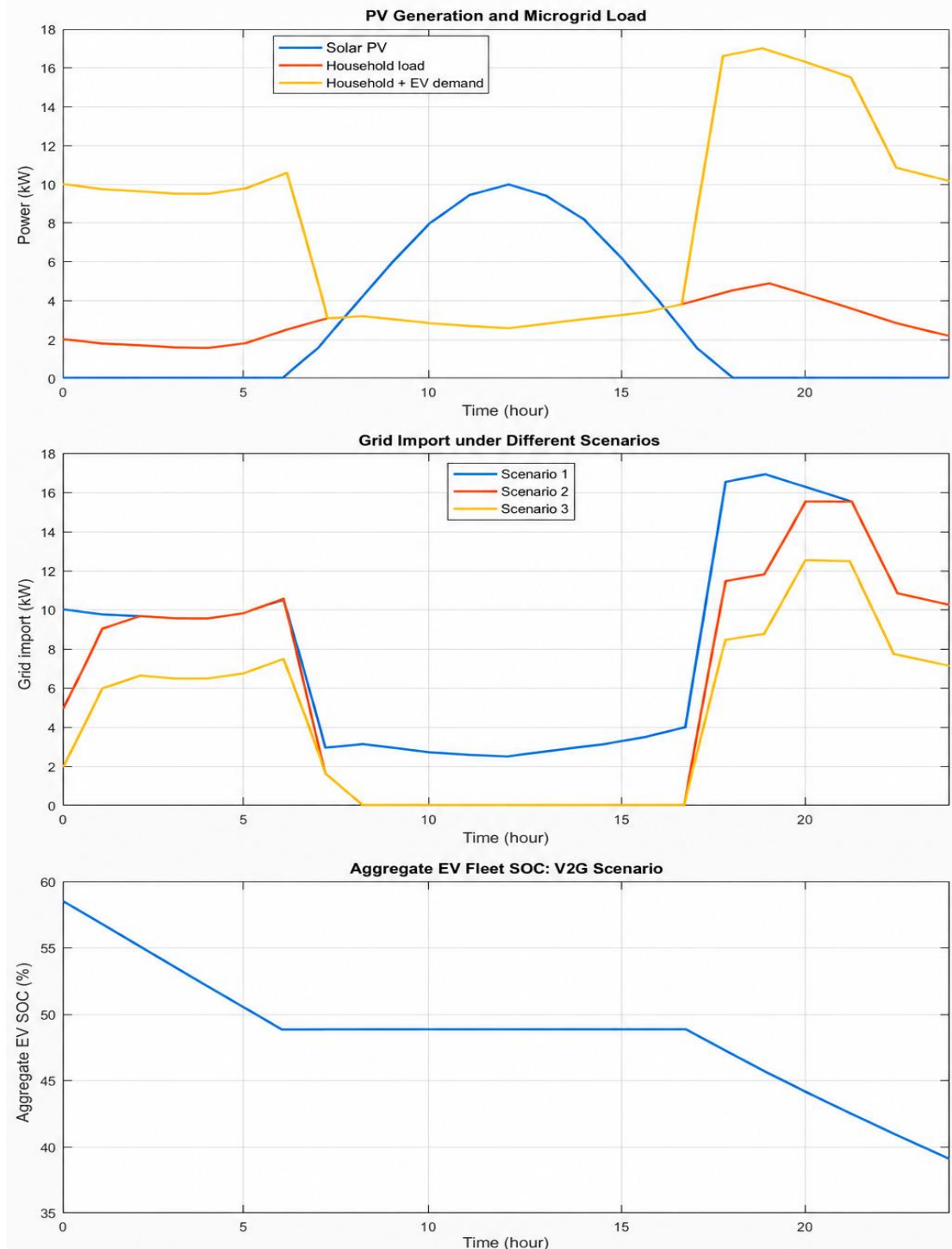


Figure 4 Grid power exchanges

• Battery SOC

The BESS SOC graph illustrates energy storage and discharge behaviour during the daily operating cycle.

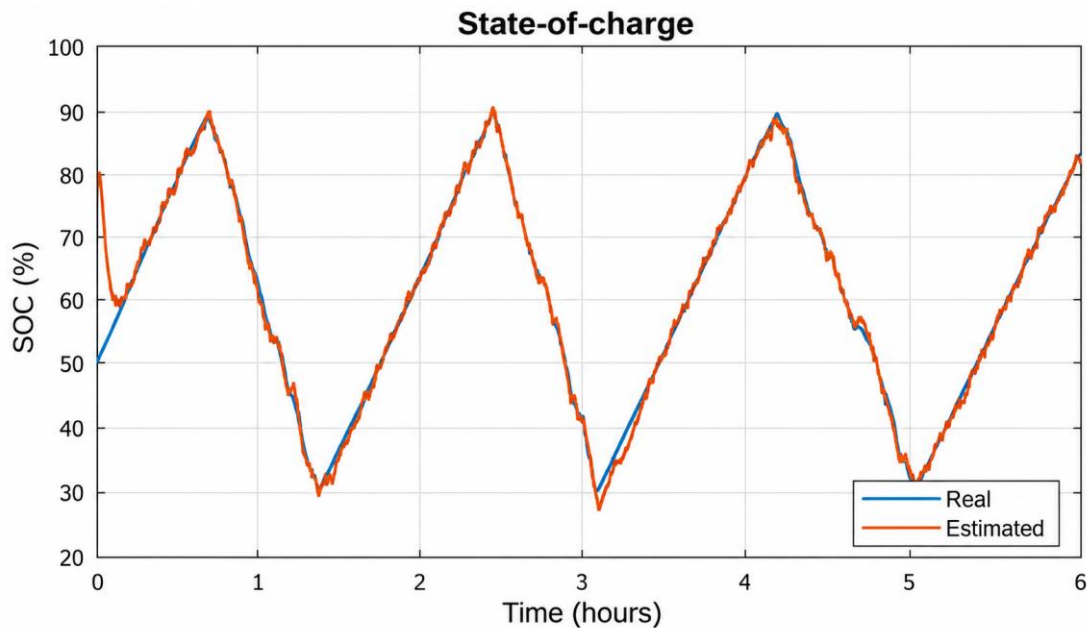


Figure 5 Battery SOC

• Carbon emission comparison

The bar chart compares operational emissions attributable to grid imports in all three scenarios.

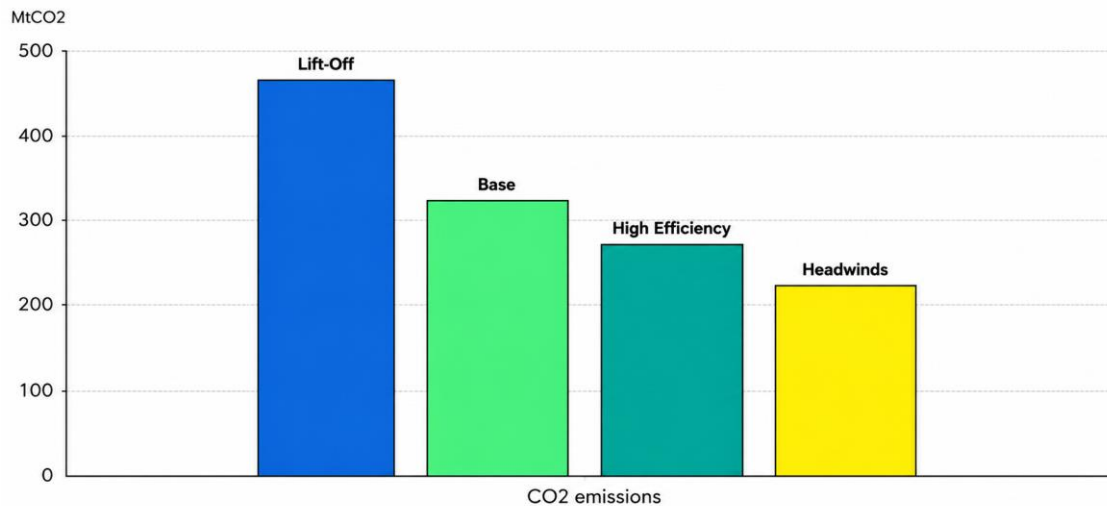


Figure 6 CO2 emissions

VII. DISCUSSION

A. Environmental Implications

The proposed framework enables the analysis of the interactions between renewable generation, EV charging, and bidirectional energy exchange. Renewable energy can reduce operational emissions by displacing carbon-intensive grid electricity. The use of V2G to supplement renewables in a microgrid can increase the flexibility of such a system by allowing stored energy to be supplied when demand is high [12].

The magnitude of carbon emission reductions, however, depends on the timing and source of the charging energy. A V2G system that charges when the electricity is of low carbon and discharges when the grid electricity is carbon-intensive could provide environmental benefits, assuming that conversion losses and the impacts on battery are incorporated. This study focuses on operational emissions [13]. A comprehensive lifecycle assessment would need to incorporate the emissions from the PV manufacturing, battery production, battery replacement, and charging infrastructure.

B. Technical Implications

The coordinated operation of the PV, BESS, and V2G adds extra control aspects. The EMS has to maintain the power balance while avoiding the SOC limits, the converter ratings, and the EV departure requirements.

The suggested rule-based approach is appropriate for a preliminary feasibility study, but its performance is determined by the quality of the operating rules and the accuracy of the forecasts. Forecast errors in solar production and EV connection schedules may cause unplanned grid imports or battery cycling. For more involved systems, a model predictive control or optimization-based scheduling can be considered to enhance the dispatch decisions while taking into account future operating conditions [14].

C. Economic Implications

The economic viability of V2G equipped microgrids is dictated by the interplay between electricity prices, energy conversion losses, battery degradation and the value of grid services.

While V2G can reduce peak electricity purchases under appropriate tariff structures, additional battery cycling may incur higher degradation costs. A V2G strategy that aims to minimize electricity expenditures while ignoring battery degradation may therefore overestimate its economic benefits [15]. An economic assessment should therefore account for the cost of bidirectional chargers, communication systems, battery replacement and any compensation paid to EV owners. The economic performance should also be assessed under different electricity tariff and grid export scenarios [16].

D. Battery Degradation and Operational Limitations

Battery degradation is a critical aspect of V2G systems operation over long periods. The V2G battery's capacity and internal resistance can be impacted by the repeated charge/discharge cycles, depending on its chemistry, temperature, SOC, depth of discharge and operating conditions. Recent reviews identify battery aging as a significant factor in the evaluation of V2G viability and scheduling strategies.

The proposed framework incorporates SOC and power limits but doesn't, in its basic form, model electrochemical battery aging. A degradation-aware controller should incorporate an estimated degradation cost or a validated battery aging model [17].

The EV fleet also generates uncertainty as vehicles can connect and disconnect at different times. Maintaining the required departure SOC is critical to ensure that grid services do not impact mobility requirements.

E. Limitations of the Proposed Study

A number of important limitations are associated with the proposed framework that should be considered while interpreting the results.

1. The initial model was developed using illustrative component parameters rather than experimentally characterised equipment properties.
2. The rule-based EMS cannot be guaranteed to yield globally optimal operating schedules.
3. The basic carbon accounting methodology only considers operational grid related emissions rather than full life cycle emissions.
4. Battery degradation was not explicitly calculated, unless an additional battery degradation model was implemented
5. EV availability and charging demand requires realistic mobility data for a representative assessment.
6. Detailed voltage stability, harmonic distortion, frequency regulation and protection performance require additional electrical network modelling.
7. Economic conclusions depend upon assumed electricity tariffs, equipment costs and compensation mechanisms

These limitations define the scope of the current simulation framework and identify areas of further validation required.

VIII. CONCLUSION AND FUTURE SCOPE**A. Conclusion**

This paper proposes a framework for incorporating vehicle-to-grid technology into renewable-powered microgrids to assess the potential for decreased operational carbon emissions. The proposed architecture includes solar power generation, bidirectional EV charging, stationary battery storage, grid power exchange and an energy management system.

A mathematical model is developed that describes microgrid power balance, PV generation, EV and BESS SOC dynamics, grid power exchange, operational carbon emissions and operational costs. A rule-based energy management strategy is proposed to coordinate the use of renewable energy, battery operation, EV charging and V2G discharging while meeting power and SOC constraints.

Three comparative operating scenarios are defined: conventional grid-connected EV charging, EV charging powered by renewables and a stationary battery storage, and V2G-enabled operation of a renewable-powered microgrid. This framework can be used to evaluate the contributions of the integration of renewable energy and V2G operations separately and assess their impact on CO₂ emissions and operational costs. The proposed methodology provides a foundation for MATLAB/Simulink-based assessment of grid electricity consumption, renewable energy utilization, CO₂ emissions and operational costs. However, the actual reduction in CO₂ emissions, economic benefit and increase in the use of renewable energy must be established through validated simulation or experimental results. Therefore, the framework should be regarded as a basis for quantitative investigation rather than evidence of a predetermined percentage improvement.

B. Future Scope

Future work might extend this framework in several directions:

1. **Optimization-based energy management:** Develop a model predictive control or mixed-integer optimization approach to improve the coordination of PV, BESS and EV charging.
2. **Battery degradation modelling:** Incorporate temperature-dependent electrochemical or empirical battery aging models to quantify the long-term effects of V2G cycling.
3. **Uncertainty modelling:** Include probabilistic solar forecasting, uncertain EV arrival times and stochastic charging demand.
4. **Multi-objective optimization:** Simultaneously minimize operational carbon emissions, electricity expenditure, peak demand and battery degradation.
5. **Grid stability assessment:** Evaluate voltage regulation, frequency response, reactive power support and power quality under V2G operation.
6. **Lifecycle carbon assessment:** Extend the operational carbon model to include the embodied emissions of PV modules, EV batteries, stationary storage and power electronic converters.
7. **Real-time validation:** Implement the EMS using hardware-in-the-loop testing or a laboratory microgrid to evaluate its practical performance.
8. **Indian microgrid applications:** Investigate the proposed system using regional solar irradiance, electricity tariffs, grid emission factors and EV charging profiles relevant to Indian distribution networks.

These extensions would help establish the technical, economic and environmental feasibility of V2G-enabled renewable-powered microgrids under realistic operating conditions.

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