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ACADEMY FOR CONTINUING EDUCATION

The Role of Bidirectional Electrical Vehicle Chargers in Enhancing Variable Renewable Energy Integration into the Electric Grid

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Univ. Prof. Dr. DI. Reinhard Haas

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Vienna, 25.11.2024

Affidavit

I, **MOHAMMAD SAFA ALSALKINI BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE ROLE OF BIDIRECTIONAL ELECTRICAL VEHICLE CHARGERS IN ENHANCING VARIABLE RENEWABLE ENERGY INTEGRATION INTO THE ELECTRIC GRID", 63 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Signature

Preface/Acknowledgment

First and foremost, I express my deepest gratitude to Allah, the Most Merciful and Most Compassionate, for blessing me with the strength, wisdom, and resilience to undertake and complete this journey. Through His divine guidance and grace, I have persevered and reached this significant milestone.

I am profoundly thankful to my esteemed supervisor, Univ. Prof. Dr. DI. Reinhard Haas, for his unwavering support, insightful advice, and tireless dedication throughout the course of this research. His invaluable guidance and expertise have been a cornerstone of my academic development, and I am sincerely grateful for the time and effort he has invested in this work.

To my beloved family, I owe the deepest gratitude. To my dear wife, who has been my pillar of strength and unwavering support through every challenge, and to my four wonderful children, whose love and patience have been a constant source of motivation. My eldest son, Jawad, your maturity has been a blessing; my second son, Yamen, your enthusiasm kept me going; my daughter, Muna, your bright spirit has always brought joy, and to my youngest daughter, Layan, your innocent presence has given me a renewed sense of purpose. Each of you has been a light in this journey, and your unwavering belief in me has made this achievement possible.

I am equally grateful to my siblings, whose support has always been a source of comfort. To my brother and sisters, thank you for standing by me with your constant encouragement and understanding. Your presence in my life has always reminded me of the importance of family, and I am deeply appreciative of the care and motivation you have given me throughout this process.

Lastly, I remember and honor the memory of my late parents, whose enduring love and values continue to guide me even in their absence. Though they are no longer with me, their influence remains profound, and I carry their legacy with pride in all that I do.

This work stands as a testament to the support, love, and encouragement of everyone who has been part of my life during this journey. My heartfelt thanks to all of you.

Mohammad Safa AlSalkini

Abstract

The rise in electric vehicles (EVs) and Variable Renewable energy sources such as solar and wind has introduced both opportunities and challenges for the modern power grid. The variability of Variable Renewable energy and the growing electricity demand from EVs strain the grid's capacity.

This thesis proposes a bidirectional EV charger system integrated into the grid that enables both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations.

By using EV batteries as distributed energy storage units, the system balances energy flows between EVs, Variable Renewable energy sources, and grid demand.

A detailed system design is developed and simulated using MATLAB/Simulink under various grid conditions, including peak demand periods, low and high Variable Renewable energy generation, and diverse load profiles typical in urban environments such as Vienna, Austria.

The system includes an advanced Energy Management System (EMS) that dynamically manages energy flows between the grid, Variable Renewable sources, and EVs.

Key results show that integrating bidirectional EV chargers into urban power grids significantly enhances grid stability, improves the utilization of Variable Renewable energy, and mitigates peak load impacts.

The system also helps prevent curtailment of Variable Renewable energy and provides ancillary services such as frequency regulation and voltage support. Additionally, a cost-benefit analysis shows that while initial investments in bidirectional chargers and infrastructure are high, the long-term benefits, including grid flexibility and carbon footprint reduction, outweigh the costs.

This thesis also provides recommendations for deploying V2G technologies in urban settings, considering regulatory, economic, and technical challenges.

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1. Introduction

1.1 Background

The transition to Variable Renewable energy sources is a critical element in achieving global carbon reduction targets. "The European Union (EU), through its European Green Deal initiative, has set a target to cut greenhouse gas emissions by at least 55% by the year 2030" (European Commission, 2020: 3). Central to this transition is Incorporating energy sources such as solar, wind, and hydropower into national grids forms a critical step in advancing this transition. However, the intermittent nature of Variable Renewable energy poses significant challenges for grid stability. Solar power is available solely during daylight, while wind energy fluctuates based on weather conditions, leading to periods of Excess generation or under-generation. These fluctuations make it difficult for grid operators to maintain a balance between supply and demand.

Simultaneously, the increasing use of electric vehicles (EVs) offers significant potential while also introducing new complexities to the power grid. EVs add substantial demand to electricity networks, particularly during peak charging periods, which can strain grid capacity. Electric vehicles (EVs), however, can serve as decentralized energy storage systems. Through Vehicle-to-Grid (V2G) technology, EVs can absorb excess energy during periods of high Variable Renewable generation and discharge stored energy during periods of high demand, thus offering a dynamic solution to grid imbalances.

This research focuses on developing and simulating a bidirectional EV charger system capable of supporting both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) energy flows. By optimizing energy flows between EVs, Variable Renewable energy sources, and the grid, the system can mitigate the variability of Variable Renewable energy and enhance grid stability.

The research focuses on urban environments like Vienna, Austria, which has set ambitious goals to achieve 100% Variable Renewable energy by 2030. The research further examines the financial and ecological impacts of incorporating bidirectional EV chargers into the power grid.

1.2 Research Problem

The main problem with integrating Variable Renewable energy into the grid is its variability. Solar and wind energy, unlike conventional fossil fuel plants, are inherently unpredictable and fluctuate based on environmental conditions.

This results in periods of Excess generation (when Variable Renewable energy output exceeds demand) and under-generation (when demand exceeds Variable Renewable output). The mismatch between generation and consumption threatens grid stability and increases reliance on backup fossil fuel plants, undermining the environmental benefits of Variable Renewable energy.

Energy storage systems (ESS) provide an effective means of managing energy, storing excess energy during periods of low demand and releasing it when the demand surpasses supply. Among various ESS options, EV batteries offer a highly scalable and distributed solution. When aggregated, EVs can function as a virtual power plant, providing grid services such as load balancing, peak shaving, frequency regulation, and backup power. However, the widespread implementation of bidirectional EV chargers that support both V2G and G2V operations presents technical challenges, particularly in the areas of power electronics, control systems, communication infrastructure, and battery management.

This thesis focuses on designing and analyzing a bidirectional EV charger system that addresses these technical challenges while optimizing energy flows between EVs, Variable Renewable energy sources, and the grid.

1.3 Research Objectives

The objectives of this thesis are:

1. To design a bidirectional EV charger system that integrates with the grid and Variable Renewable energy sources to facilitate **V2G** and **G2V** energy flows.
2. To create an advanced **Energy Management System (EMS)** that efficiently manages the charging and discharging processes of EV batteries by leveraging real-time data from the grid and renewable energy sources.

3. To evaluate the impact of the system on **grid stability**, **Variable Renewable energy utilization**, and **peak demand management** through simulations in **MATLAB/Simulink**.

1.4 Research Questions

This research aims to answer the following questions:

1. How can bidirectional EV chargers be designed and implemented to optimize energy flows between EVs, the grid, and Variable Renewable energy sources?
2. What technical challenges arise from integrating **V2G** and **G2V** operations, particularly in the areas of **power electronics**, **energy management**, and **communication systems**?
3. How can the proposed system enhance grid stability and Variable Renewable energy utilization in urban environments like **Vienna, Austria**?

1.5 Thesis Structure

This thesis is organized as follows:

- **Chapter 2: Literature Review** – This chapter offers a detailed examination of existing studies and research on bidirectional EV chargers, V2G/G2V technologies, and Variable Renewable energy integration. It explores the technical challenges and potential solutions for integrating these technologies into the modern power grid.
- **Chapter 3: System Design and Architecture** – This chapter provides a comprehensive description of the bidirectional EV charger system, detailing its technical specifications, power electronics, and the energy management framework. Key design decisions, such as inverter topology and control algorithms, are discussed.
- **Chapter 4: Methodology** – This chapter explains the approach adopted for simulating the proposed system, including data collection, simulation setup, and

model validation. It provides an overview also of the software and methodologies applied for system modeling, specifically utilizing MATLAB/Simulink.

- **Chapter 5: Simulation Results and Discussion** – The results of the simulations are presented and analyzed in this chapter, with a focus on evaluating the system's performance under various grid conditions, including scenarios of high and low Variable Renewable energy generation.

- **Chapter 6: Conclusion and Recommendations** – This final chapter consolidates the research's primary findings, addresses the limitations of the system's current design, and suggests directions for future studies and practical implementation.

2. Literature Review

2.1 Introduction

The integration of Variable Renewable energy into the grid introduces technical challenges due to the unpredictable nature of wind and solar power. A range of innovative technologies has been created to tackle these challenges, with Vehicle-to-Grid (V2G) systems emerging as a promising solution. Vehicle-to-Grid (V2G) technology allows electric vehicles to transfer stored energy back to the grid, offering critical services like frequency regulation, peak load management, and emergency backup power. However, the successful deployment of V2G requires advancements in power electronics, communication protocols, and control systems. (Kempton & Tomić, 2005).

Several inverter technologies have been developed to facilitate bidirectional energy flow between EVs and the grid. The most common is the full-bridge inverter topology, which allows both AC-DC and DC-AC conversions. Silicon Carbide (SiC) inverters, for instance, achieve greater efficiency and operate at higher switching speeds compared to conventional silicon-based inverters. According to Meng et al. (2019), SiC inverters can achieve efficiencies of up to 98%, making them ideal for high-power V2G applications. However, the high cost of SiC technology remains a barrier to widespread adoption. (Liu et al., 2019).

Bidirectional EV chargers serve as essential elements in V2G systems, enabling energy to move seamlessly between the EV battery and the electrical grid. Recent innovations in power electronics and advanced charging technologies have significantly enhanced the dependability and operational efficiency of these chargers. Nonetheless, several challenges persist, including high infrastructure costs, limited grid compatibility, and battery degradation concerns (Liu et al., 2019). Additionally, regulatory barriers and the absence of financial incentives for EV owners to participate in V2G programs hinder large-scale implementation. (Kempton & Tomić, 2005).

The economic viability of V2G systems has been demonstrated in pilot projects across Europe, including Denmark, where EVs were used to provide frequency regulation services to the grid. These projects have shown that V2G can reduce grid management costs by up to 10% while enhancing the integration of Variable Renewable energy

(Kempton & Tomic, 2005). However, the widespread adoption of V2G technology requires Substantial funding in infrastructure and the creation of supportive frameworks are essential for progress. Additional studies are required to investigate economically viable solutions and scalable models for V2G deployment (Lund et al., 2015).

2.2 Inverter Technologies

Bidirectional inverters are a critical component of V2G systems, allowing energy to flow in both directions between the EV battery and the grid. In G2V mode, the inverter converts AC power from the grid into DC power to charge the EV battery. In V2G mode, the system converts the stored DC energy from the battery into AC power, making it available for feeding back into the electrical grid. The effectiveness and dependability of these inverters play a vital role in ensuring the system operates optimally.

- **Full-Bridge Topology**: The full-bridge inverter Represents one of the widely utilized configurations used in bidirectional EV chargers. It is composed of four Insulated-Gate Bipolar Transistors (IGBTs) configured in an H-bridge arrangement, enabling both AC-to-DC and DC-to-AC energy conversion. While effective, this topology can introduce switching losses, especially at high power levels.

- **Silicon Carbide (SiC) Technology**: In recent years, Silicon Carbide (SiC)-based inverters Have become notable for their superior efficiency and ability to handle higher switching frequencies in comparison to traditional silicon-based inverters. SiC technology reduces switching losses and enables compact designs, making it ideal for high-power V2G applications. According to Meng et al. (2019), SiC inverters achieve efficiencies of up to 98%, making them highly suitable for large-scale implementations of V2G systems.

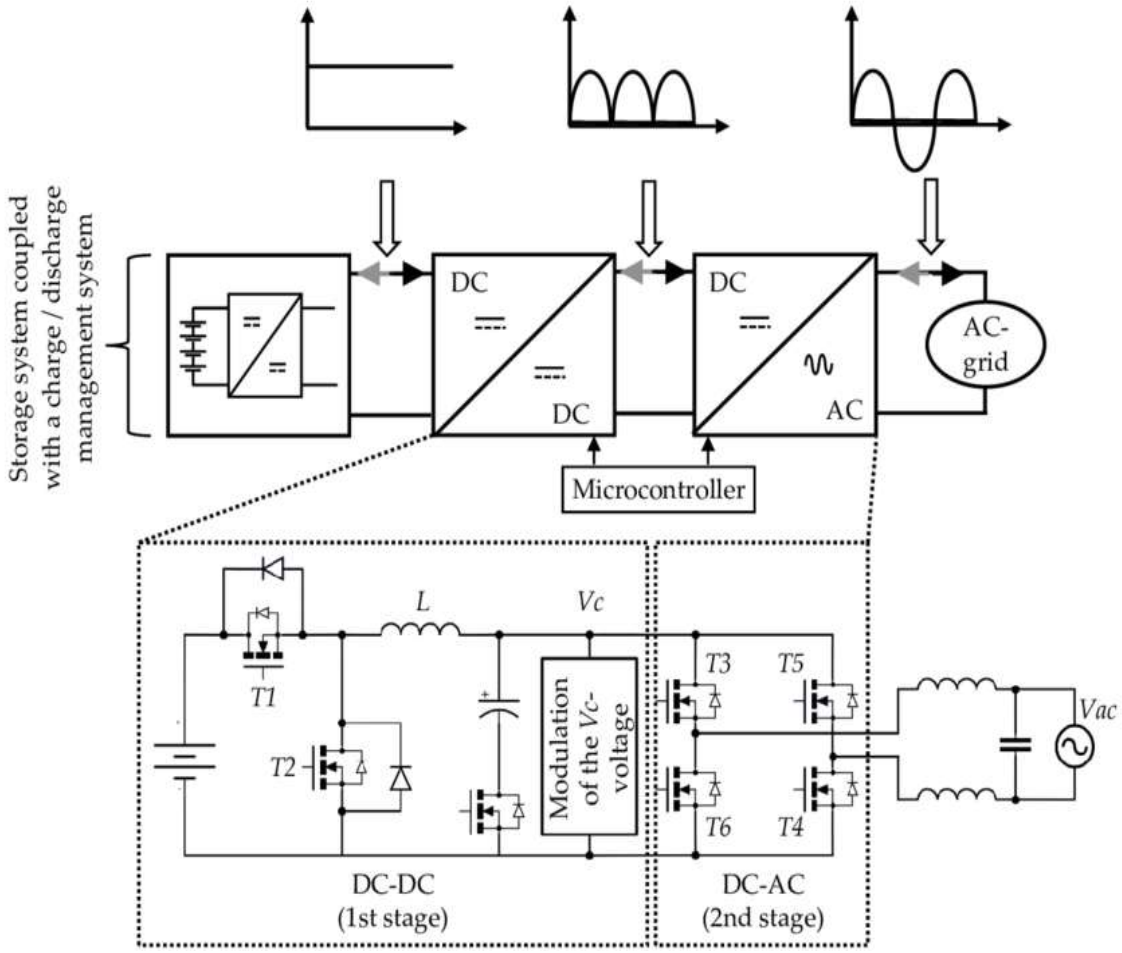

Figure 1: *Schematic diagram of a bidirectional inverter showing the AC-DC and DC-AC conversion pathways.*
Reference: *"An Innovative Bidirectional DC-AC Converter to Improve Power Quality in a Grid-Connected Microgrid" Bissey, Sébastien & Jacques, Sebastien & Reymond, Cedric & Le Bunetel, Jean-Charles. (2018).*

Table 1*: Comparison of Different Inverter Technologies for Bidirectional EV Chargers.*

Inverter Type	Efficiency (%)	Cost ($/unit)	Switching Losses (W)	Applications
Silicon-Based	92-94%	800	100-150	Small-scale EV systems
Silicon Carbide (SiC)	96-98%	1200	50-70	High-power V2G systems

References: Gao, S., Li, H., & Zhao, Y. (2019). *A comprehensive review on DC/DC converter topologies and control strategies for electric vehicles.* IEEE Access

GaN (Gallium Nitride) Inverters: Another emerging technology is Gallium Nitride (GaN)-based inverters, which offer high efficiency and fast switching capabilities. Although not yet as widespread as SiC inverters, GaN technology is promising for future bidirectional charging systems, particularly where space and weight are significant constraints.

2.3 Bidirectional EV Chargers

Bidirectional EV chargers play a pivotal role in facilitating the integration of electric vehicles (EVs) into the energy grid, particularly through Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations.

These chargers enable the transfer of energy in both directions — the grid to the vehicle and the vehicle back to the grid—enabling EVs to function as distributed energy storage units. This bidirectional energy flow helps balance grid supply and demand, especially in grids with a high proportion of Variable Renewable Energy (VRE) sources such as solar and wind (Kempton & Tomić, 2005).

***Table 2**: Features of Bidirectional EV Chargers*

Feature	Description
Power Conversion	AC to DC for charging, DC to AC for discharging
Communication Protocol	IEEE 2030.5 for real-time data exchange
Inverter Type	Silicon Carbide (SiC) Inverters
Maximum Charging Power	50 kW
Maximum Discharging Power	50 kW

Reference: *International Energy Agency (IEA). (2020)*

Advances in power electronics, control mechanisms, and communication protocols have significantly enhanced the efficiency and dependability of bidirectional chargers. Silicon Carbide (SiC) technology has enhanced the efficiency and scalability of bidirectional chargers, with SiC-based inverters achieving efficiency levels of up to 98% Attributable to their reduced switching losses and superior thermal conductivity（Meng et al., 2019）. This improvement is critical in large-scale implementations of V2G systems, especially in urban environments where peak loads and renewable energy variability present significant challenges.

However, high infrastructure costs remain a barrier to widespread adoption. Studies suggest that the initial investment for bidirectional charging infrastructure is substantially higher than that for unidirectional systems, largely due to the increased complexity of power electronics and communication requirements (Liu et al., 2019). Despite these costs, several pilot projects have demonstrated the long-term economic benefits of V2G technology, such benefits include improved grid stability and a decreased dependence on fossil fuel-powered peaking plants (Lund et al., 2015).

2.4 Vehicle-to-Grid (V2G) Technology

Vehicle-to-Grid (V2G) technology transforms electric vehicles (EVs) into dual-purpose assets, allowing them to both consume electricity and supply energy back to the grid. In periods of low electricity demand, EVs can absorb excess renewable energy, particularly during times of high wind or solar generation. [Conversely, during peak demand, EVs can discharge stored energy back into the grid, alleviating strain and helping stabilize the system]（Kempton & Tomić, 2005）.

Numerous control approaches have been suggested to achieve optimal performance of the charging and discharging schedules of EVs within a V2G framework. **Centralized control systems** typically managed by grid operators or third-party aggregators optimize the use of the fleet as a virtual power plant (VPP). However, centralized control may lead to bottlenecks due to the complexity of managing thousands of EVs simultaneously. In contrast, **decentralized control systems** provide each charger with the autonomy to make decisions based on local conditions, such as voltage or frequency deviations (Guille & Gross, 2009）.

The decentralized approach improves system resilience and adaptability but may lead to inefficiencies at the macro level without a unifying optimization algorithm.

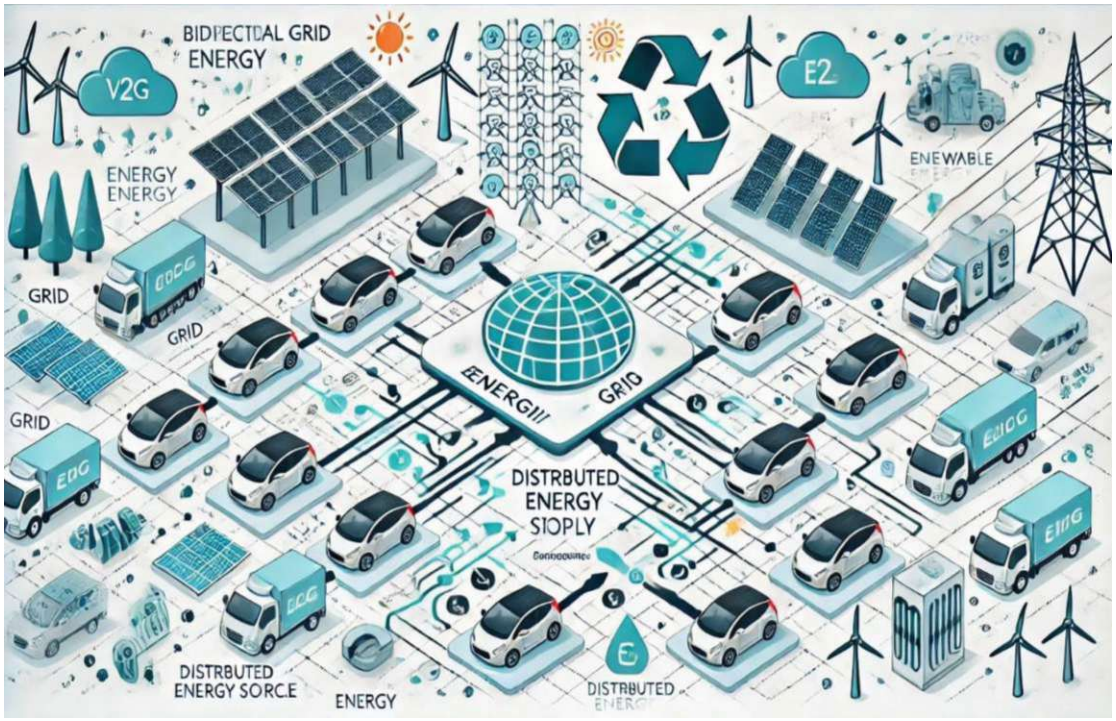

Figure 2: *Diagram showing the bidirectional flow of energy in a V2G system, with EVs acting as distributed energy storage units.*

Control Strategies for V2G

Control Strategies for V2G: The successful deployment of V2G technology relies on sophisticated control mechanisms to regulate the charging and discharging processes of multiple EVs, all while ensuring the mobility requirements of EV owners are met. These strategies include:

- **Centralized Control**: A central system, often operated by a utility or third-party aggregator, coordinates the charging and discharging schedules of EVs according to real-time grid conditions.
- **Decentralized Control**: Each EV charger operates autonomously, using local measurements (e.g., grid frequency, voltage) to make charging decisions, enhancing system resilience (Kempton & Tomic, 2005)
- **Hybrid Control**: Combines elements of centralized and decentralized control, providing a balance between system-level optimization and local autonomy.

Hybrid control systems present a promising alternative, combining both centralized oversight with decentralized, real-time decision-making at the local level. The hybrid approach balances flexibility with grid-level optimization and is gaining traction in pilot projects across Europe and North America (Noel et al., 2019).

2.5 Integration of Variable Renewable Energy into the Grid

The integration of **Variable Renewable energy sources (RES)** such as **solar** and **wind** into the grid presents significant challenges due to their variability. **Solar power** is only generated during the day, and **wind power** is subject to changes in weather conditions, making it difficult for grid operators to maintain a balance between energy supply and demand. **Energy storage systems (ESS)** play a vital role in addressing these challenges by storing surplus energy from Variable Renewable sources during low-demand periods and supplying it during peak demand time. **EV batteries**, when integrated into the grid through **V2G technology**, can provide a large, distributed energy storage Reference that complements other forms of ESS (Lund et al., 2015).

***Table 3**: Summary of Challenges in Variable Renewable Energy Integration and Potential Solutions Through V2G.*

Challenges in Variable Renewable Energy Integration	Description	Potential Solutions Through V2G
Intermittency of Variable Renewable Energy	Solar and wind power are inherently variable, relying on weather conditions, which can result in instances of overproduction or insufficient generation.	V2G technology allows EVs to function as decentralized energy storage systems, storing excess energy during times of high renewable energy generation and feeding electricity back into the grid during periods of low production.
Grid Stability and Frequency Regulation	Fluctuations in Variable Renewable energy can cause frequency deviations and grid instability.	V2G provides frequency regulation services by allowing EVs to charge or discharge in response to grid frequency changes, helping to maintain grid stability.

Peak Load Management	High Variable Renewable generation during off-peak hours can lead to grid congestion, while peak demand times may coincide with low Variable Renewable generation.	V2G enables peak load shaving by discharging EVs during peak demand periods, reducing strain on the grid and minimizing the need for fossil fuel-based peaking power plants.
Energy Curtailment	Excess Variable Renewable energy during periods of low demand can lead to energy curtailment, wasting potential clean energy.	V2G technology enables EVs to supply stored energy to the grid during periods of high demand, helping to address demand-supply imbalances and contribute to a more stable and reliable power system.
Lack of Energy Storage	The absence of adequate energy storage solutions limits the ability to store excess Variable Renewable energy for later use.	V2G leverages the existing EV battery infrastructure as a distributed energy storage network, reducing the need for additional grid-scale storage investments.
Demand-Supply Mismatch	The production of Variable Renewable energy often occurs at times that do not coincide with periods of peak electricity demand.	V2G allows EVs to discharge stored energy back into the grid during high-demand periods, balancing the demand-supply mismatch and ensuring a more reliable power supply.
Grid Congestion	High Variable Renewable energy penetration can cause localized grid congestion, affecting power quality.	V2G can provide localized support by discharging energy where it is needed, alleviating grid congestion and improving power quality in areas with high Variable Renewable penetration.
Infrastructure and Integration Costs	Integrating Variable Renewable energy demands extensive upgrades to grid infrastructure and the implementation of advanced storage technologies.	V2G utilizes the existing EV and charging infrastructure, reducing the need for new investments while providing a cost-effective way to enhance grid flexibility and stability.
Battery Degradation Concerns	Frequent use of EV batteries for grid services can cause battery degradation, which may influence the willingness of EV owners to engage in	Advanced battery management systems (BMS) in V2G can optimize charging/discharging cycles to minimize battery wear, and incentives can be

	V2G programs. However, advanced Battery Management Systems (BMS) can optimize charge and discharge cycles to reduce wear, while incentives can encourage participation.	provided to EV owners for their participation.

References:

1. *Kempton, W., & Tomić, J. (2005). Vehicle-to-grid technology: An overview of enabling technologies. Energy Policy, 33(11), 1195-1207.*
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9. *Noel, L., Sovacool, B. K., Kester, J., & de Rubens, G. Z. (2019). Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility.*
10. *IEEE 2030.5 (Smart Energy Profile 2.0).*
11. *ISO/IEC 15118.*

This table highlights how V2G technology can address key challenges in Variable Renewable energy integration by leveraging EVs as distributed energy storage units, thus enhancing grid stability, optimizing Variable Renewable energy utilization, while also lessening the requirement for further investments in infrastructure.

2.6 Communication and Control Systems

The communication infrastructure in V2G systems is critical for ensuring that EVs can effectively interact with the grid. [Two-way communication between EVs, charging stations, and grid operators facilitates real-time data sharing, enabling the grid to adapt promptly to fluctuations in energy demand or supply.] (Liu et al., 2019).

The IEEE 2030.5 standard, also known as Smart Energy Profile 2.0, is one of the leading communication protocols that enable secure data exchange between EVs, chargers, and the grid. This protocol supports demand response programs, peak shaving, and the

integration of VREs by allowing EVs to participate actively in grid stabilization efforts. However, a key challenge remains ensuring the cybersecurity of this communication infrastructure. The expansion of V2G systems introduces new vulnerabilities that could potentially be exploited by cyberattacks, necessitating robust encryption, authentication, and data management protocols (IEEE, 2020).

Ongoing research is exploring the application of blockchain technology in V2G systems to enhance transaction security between EVs and the grid. [Blockchain provides a decentralized and secure method that is resistant to tampering to record energy exchanges, making it easier to track contributions and compensate EV owners for providing energy back to the grid] (Noel et al., 2019).

2.7 Economic and Regulatory Challenges in V2G Adoption

While bidirectional EV chargers offer significant potential, the implementation of V2G technology faces considerable economic and regulatory challenges. Initial infrastructure costs, including advanced chargers and communication protocols, represent a significant barrier to large-scale adoption. Moreover, regulatory frameworks in many regions are still evolving to accommodate bidirectional energy flows, with grid interconnection policies often lacking provisions for distributed energy storage.

Incentivizing EV owners to participate in V2G services also remains a challenge, as current market structures do not always compensate for the wear and tear on EV batteries. Real-world examples, such as the pilot programs in California and Denmark, demonstrate that supportive policies and financial incentives are key to fostering widespread adoption of V2G technologies.

3. System Design and Architecture

3.1 Bidirectional EV Charger System Architecture

The proposed bidirectional EV charger system enables two-way energy flow between the electric grid and electric vehicles (EVs), integrating Variable Renewable energy sources to optimize energy usage. The system consists of several key components, including:

- **Bidirectional Inverter**: Utilizes a Silicon Carbide (SiC)-based inverter for efficient AC/DC conversion.
- **Energy Management System (EMS)**: A central control unit that manages energy flows between EVs, the grid, and Variable Renewable energy sources, using real-time data to make informed decisions on charging and discharging cycles.
- **Communication Interface**: Facilitates real-time data exchange between the EVs, the grid, and Variable Renewable energy sources using the IEEE 2030.5 protocol.

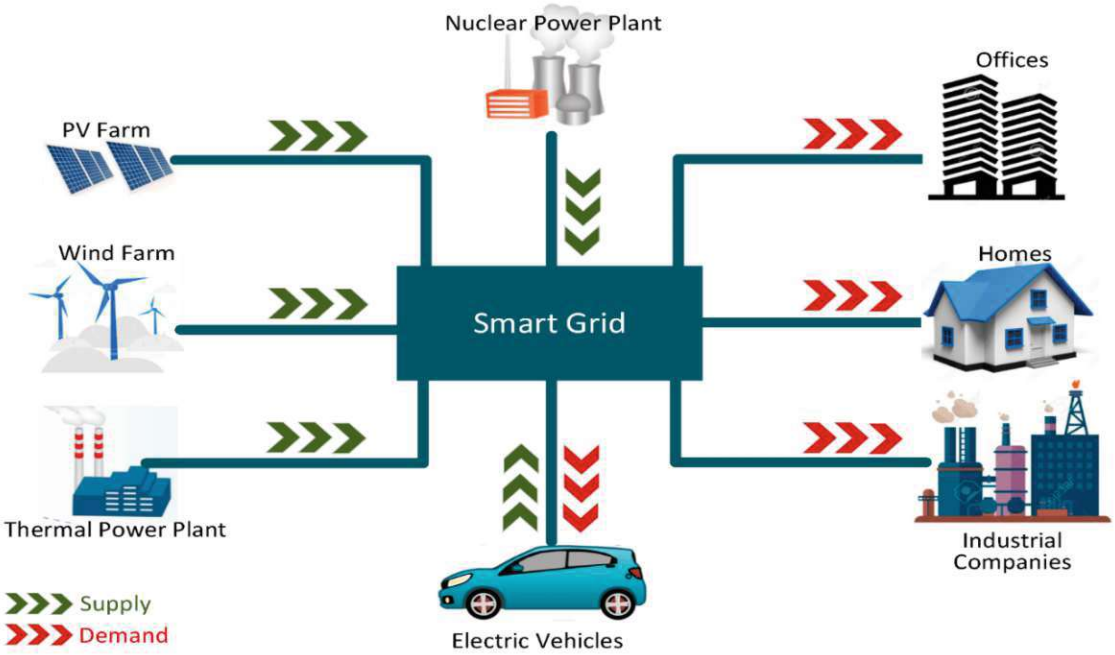

Figure 3: *System architecture diagram showing the interaction between the grid, Variable Renewable energy sources, and EVs.*

- **Control and Protection System**: Ensures system safety by tracking critical parameters like voltage, current, and temperature, safeguarding both the battery and the grid infrastructure.

The bidirectional EV charger is designed to interact seamlessly with the grid and Variable Renewable energy sources. In G2V mode, it draws power from the grid or Variable Renewable sources to charge the EV battery. In V2G mode, it discharges the stored energy back into the grid during peak demand periods, providing ancillary services such as frequency regulation and peak load shaving.

3.2 Bidirectional Inverter Design

The bidirectional inverter serves as the core component of the charger system, facilitating the conversion of AC power from the grid to DC power for EV battery charging, and vice versa for grid feedback. The proposed system incorporates a Silicon Carbide (SiC)-based inverter, chosen for its exceptional efficiency, rapid switching capabilities, and effective thermal management.

3.2.1 Inverter Topology

A full-bridge topology is utilized in the SiC inverter, featuring four SiC MOSFETs arranged in an H-bridge configuration. This topology allows the inverter to perform both AC-DC and DC-AC conversions efficiently.

Silicon Carbide (SiC) IGBTs are favored for their superior efficiency and capability to function at elevated switching frequencies, surpassing the performance of traditional silicon-based devices. This reduces the size of passive components (inductors and capacitors) and improves the overall efficiency of the system.

The full-bridge inverter generates an AC output voltage, which can be expressed as:

Equation 1: output AC voltage of the full-bridge inverter

$$V_{AC}(t) = V_{DC} \times \sin(\omega t) \text{ volt}$$

Where:

- $V_{AC}(t)$ (volt) is the output AC voltage.
- V_{DC} (volt) is the DC input voltage from the EV battery.

- $\omega = 2\pi f$ (Hertz) is the angular frequency of the AC output. With f being the output frequency.
- t is the time.

The inverter is controlled through Pulse Width Modulation (PWM) techniques, which are used to adjust and stabilize the output voltage and current.

PWM Control:

The inverter employs a high-frequency PWM signal managing the switching operations of the SiC MOSFETs. The PWM signal is generated by comparing a reference sine wave (grid voltage) with a high-frequency triangular wave. The resulting modulated signal controls the gates of the MOSFETs to achieve the desired AC output waveform.

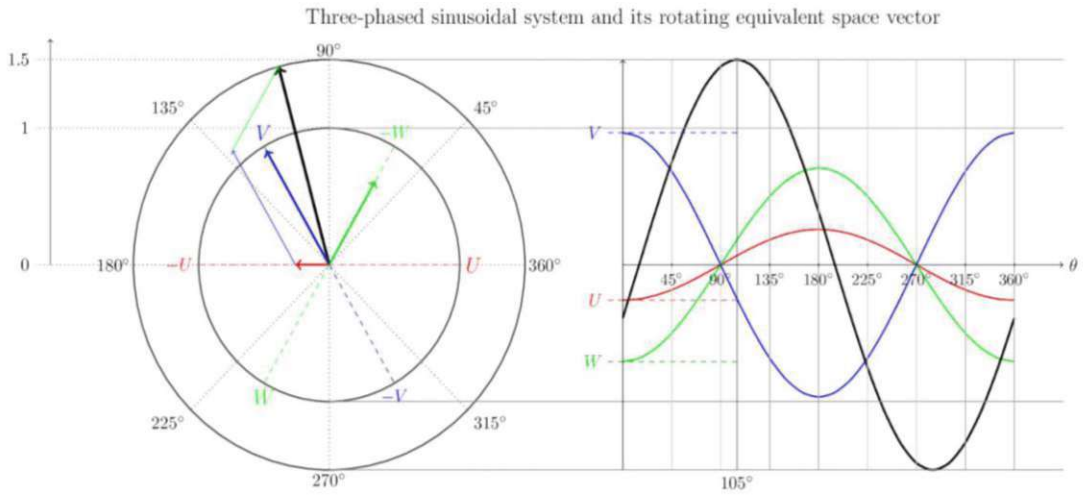

Figure 4: *the operation of a full-bridge inverter using SVPWM for bidirectional energy flow.*
***Reference** : https://www.switchcraft.org/*

3.2.2 Inverter Efficiency and Thermal Management

The efficiency of the inverter, η_{inv} %, is calculated using the equation:

Equation 2: inverter efficiency %

$$\eta inv = \frac{P_{out}}{P_{in}} \times 100\ \%$$

Where:

- P_{out} is the output power from the inverter (watts or kilowatts).
- P_{in} is the input power to the inverter (watts or kilowatts).

In this system, the SiC inverter operates with an efficiency of approximately 97% (Liu et al., 2019). The high efficiency of SiC inverters results from their low switching losses and high thermal conductivity, which allows for better heat dissipation. Proper thermal management Plays a vital role in ensuring the inverter's reliability and extending its operational lifespan. The design integrates heat sinks and cooling fans to manage and remove excess thermal energy generated during operation.

***Table 4**: Inverter Parameters for the Bidirectional EV Charger System*

Parameter	Value	Unit
Rated Power	50	kW
Inverter Efficiency	97	%
Switching Frequency	20	kHz
Maximum Voltage	400	V
Cooling System	Forced Air	-

References: Hava & Un (2009) and Mohan et al. (2003)

3.3 Energy Management System (EMS) Design

The Energy Management System (EMS) is the control center of the bidirectional EV charger system. It optimizes the charging and discharging cycles of EV batteries based on real-time grid conditions, Variable Renewable energy availability, and user preferences. The EMS consists of the following components:

- **Data Acquisition Unit**: Collects real-time data on grid demand, Variable Renewable energy generation, and EV battery status.
- **Optimization Algorithm**: Implements an optimization algorithm (e.g., fuzzy logic, predictive control) to determine the optimal charging/discharging strategy based on current grid conditions.

- **Control Unit**: Executes the control actions determined by the optimization algorithm, adjusting the power flow between the grid, Variable Renewable sources, and EVs.
- **User Interface**: Allows users to set preferences such as charging schedules, maximum charging power, and desired state-of-charge (SOC).

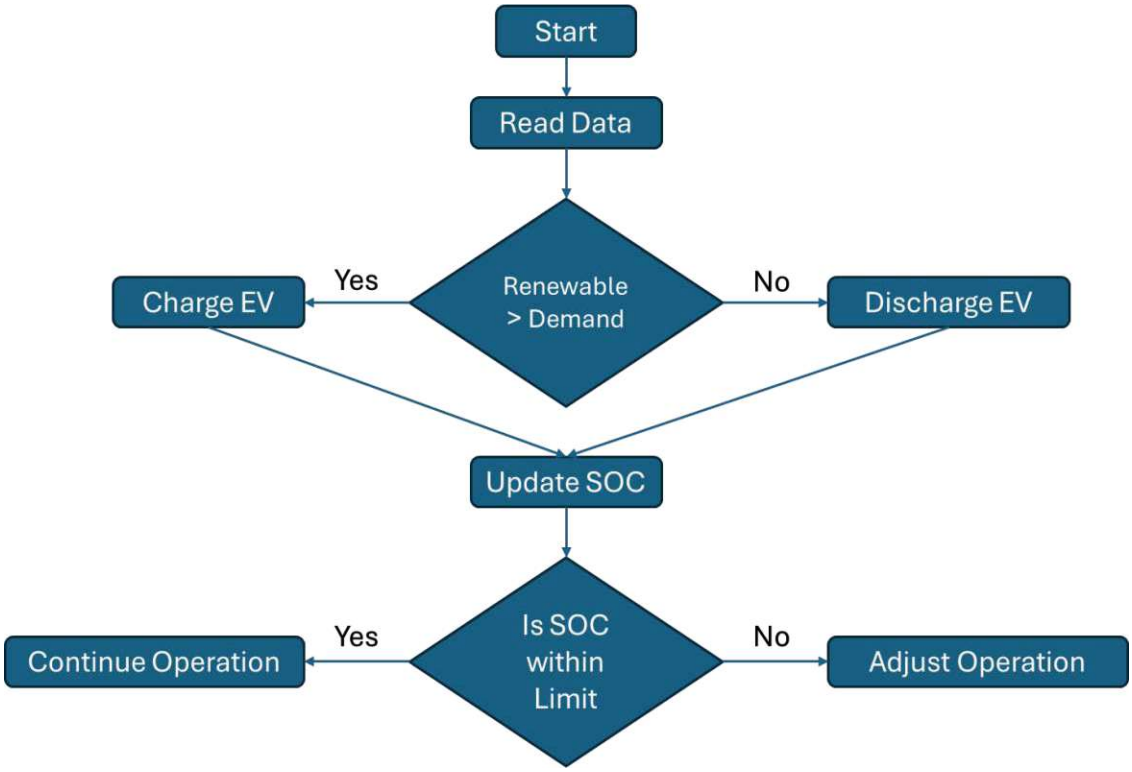

Figure 5: *Flowchart illustrating the EMS decision-making process for optimizing energy flow between the grid, Variable Renewable energy sources, and EVs*.

3.3.1 EMS Control Algorithm

Several control algorithms have been developed to manage the complex interactions between EVs, the grid, and Variable Renewable energy sources. Some commonly used algorithms include:

- **Rule-Based Control**: This approach uses predefined rules and thresholds to make decisions. For instance, the EMS might charge EVs when Variable

Renewable energy generation exceeds a certain threshold and discharge them when grid demand is high.

- **Model Predictive Control (MPC)**: MPC optimizes the charging and discharging schedule of EVs over a future time horizon based on predictions of grid demand, Variable Renewable energy generation, and electricity prices. It offers a more flexible and adaptive approach compared to rule-based control.

- **Machine Learning Algorithms**: Advanced EMSs can use machine learning techniques to predict Variable Renewable energy generation and grid demand, improving the decision-making process for charging and discharging cycles (Liu et al., 2019).

***Table 5**: Comparison of EMS Control Algorithms for V2G Systems*

Control Algorithm	Description	Advantages	Limitations
Rule-Based Control	Uses predefined rules for decision-making	Simple, easy to implement	Not adaptive to changing conditions
Model Predictive Control	Optimizes over a future time horizon	Adaptive, can handle constraints	Computationally intensive
Machine Learning	Uses data-driven models for prediction	High accuracy in predictions	Requires large datasets

***References:** Karmiris, G., & Papadopoulos, M. P. (2019). Energy management strategies for grid-connected electric vehicles*

The EMS employs a control algorithm that dynamically optimizes the charging and discharging of EV batteries, aiming to enhance the utilization of Variable Renewable energy and maintain grid stability. The algorithm considers several factors such as:

- **Grid Demand**: The EMS monitors real-time grid demand and adjusts the power flow accordingly.

- **Variable Renewable Energy Availability**: The EMS prioritizes the use of Variable Renewable energy for charging EVs when available.

- **Battery State-of-Charge (SOC):** The EMS ensures that the EV batteries maintain an optimal SOC to provide grid services while meeting the mobility needs of the users.

The control algorithm can be expressed mathematically as follows:

If $P_{\text{Variable Renewable}} > P_{\text{demand}}$, then: Charge EV batteries with the excess Variable Renewable energy:

$P_{\text{charge}} = (P_{\text{Variable Renewable}} - P_{\text{demand}}) \times \eta_{\text{charge}}$

If $P_{\text{demand}} > P_{\text{renewable}}$, then: Discharge EV batteries to the grid:

$P_{\text{discharge}} = (P_{\text{demand}} - P_{\text{renewable}}) \times \eta_{\text{discharge}}$

Where:

- $P_{\text{Variable Renewable}}$ is the Variable Renewable energy generation.
- P_{demand} is the grid demand.
- η_{charge} and $\eta_{\text{discharge}}$ Refer to the efficiencies associated with the charging and discharging processes of EV batteries.

The optimization objective of the EMS can be expressed as:

Equation 3: optimization objective of the EMS

$$\min \sum_{t=1}^{N} [\alpha . P_{grid}(t) + \beta . SOC_{deviation}(t)$$

Subject to:

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$

Where:

- $P_{grid}(t)$ (watts or kilowatts) represents the power transferred to or from the grid at a specific moment in time t.
- $SOC(t)$ (%) is the state of charge of the EV battery.
- α and β are weighting factors.
- SOC_{min} and SOC_{max} are the minimum and maximum allowable SOC

3.4 Communication and Control System

The communication and control framework in the bidirectional EV charger system is engineered to provide secure, real-time, and seamless coordination among the grid, charging infrastructure, and EVs. Based on the **IEEE 2030.5** standard, this system facilitates the exchange of information and control signals necessary for efficient V2G and G2V operations.

The IEEE 2030.5 standard, also known as the **Smart Energy Profile 2.0 (SEP2)**, is a crucial framework that allows for **interoperable and secure communication** within smart grids. It ensures that various components, including the EVs, charging infrastructure, and grid operators, can communicate effectively to optimize energy flows.

3.4.1 Communication system components:

- **Smart Meters**: installed at the charging stations and the EVs to monitor real-time energy flows, including the energy either consumed from or delivered back to the grid.

  These systems consistently monitor key metrics such as current, voltage, power output, and energy usage or production.

  The collected data is transmitted to the EMS through the IEEE 2030.5 communication protocol. The real-time data exchange enables the EMS to make informed decisions regarding the charging and discharging cycles of EVs.

  In addition to basic metering functions, these smart meters can also detect power quality issues and provide **time-of-use (TOU)** data, allowing the EMS to adjust operations based on grid conditions and energy tariffs.

- **Charging Station Controllers**: responsible for managing the operation of the **bidirectional inverter**. They receive commands from the EMS and execute control actions to modulate the inverter's charging or discharging mode.

  The controllers adjust the **pulse width modulation (PWM)** signals sent to the inverter's switches, controlling the direction and magnitude of power flow. For example, during G2V operations, the controllers ensure the inverter converts AC

power from the grid to DC power for EV charging. Conversely, during V2G operations, they manage the conversion of DC power from the EV batteries to AC power for grid support.

The controllers also enforce safety protocols, including **islanding detection** and **grid synchronization**, to ensure that the power exchange between the EVs and the grid is safe and complies with grid regulations.

- **Grid Operator Interface**: is a critical component that allows grid operators to interact with the EMS. It provides the grid operator with a platform to send control signals and operational constraints to the EMS for grid stabilization purposes.

  These signals may include commands to **ramp up** or **ramp down** V2G operations based on grid conditions, such as peak load periods, frequency deviations, or voltage regulation needs.

  By sending signals to the EMS, the grid operator can optimize the grid's performance by leveraging the distributed energy storage capability of the EV fleet. For instance, during a frequency drop, the operator can instruct the EMS to initiate V2G operations, supplying power back to the grid to restore frequency stability.

  The grid operator interface employs **encryption** and **authentication** methods defined by the IEEE 2030.5 standard to ensure secure and reliable communication, preventing unauthorized access and data tampering.

3.4.2 Data Flow and Control Mechanism

The communication system enables a bidirectional flow of data between the components:

- **EMS to Charging Stations**: The EMS sends control commands to the charging station controllers, dictating the charging or discharging cycles based on real-time grid and Variable Renewable energy data.
- **Charging Stations to EMS**: Charging stations report back the status of the EVs, including SOC levels and power exchange rates.

- **Grid Operator to EMS**: The grid operator provides grid status updates and operational directives to the EMS, allowing coordinated efforts to maintain grid stability.

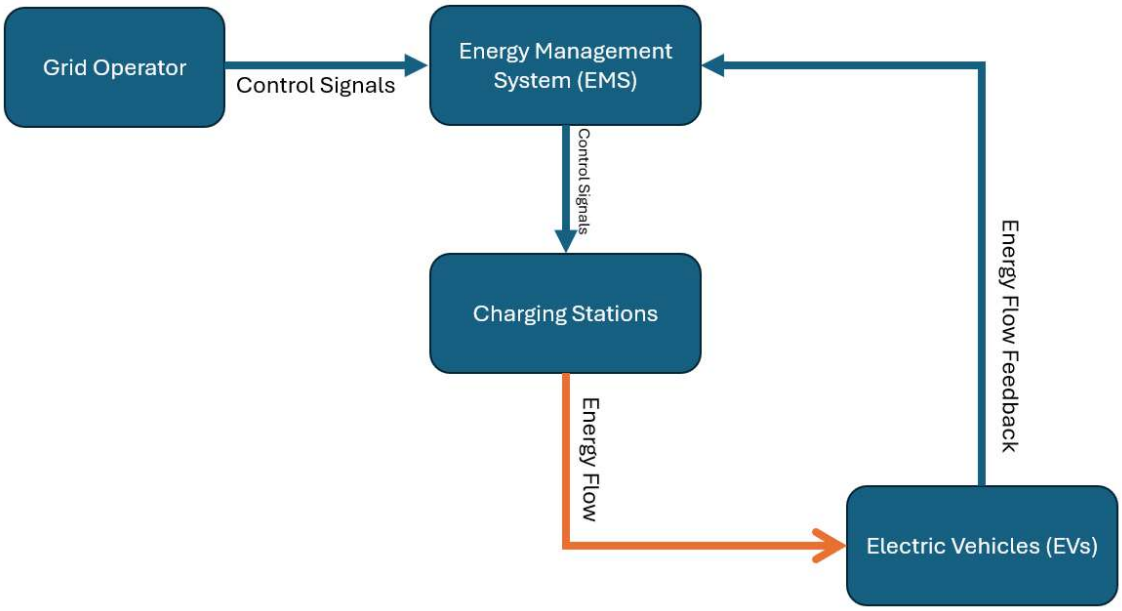

Figure 6 : *Block diagram of the communication system, illustrating data flow between the grid operator, EMS, charging stations, and EVs.*

4. Simulation and Methodology

4.1 Data Collection and Setup

The methodology for this thesis involves the design, simulation, and analysis of a bidirectional EV charger system using MATLAB/Simulink. Data on grid demand and Variable Renewable energy generation were sourced from the **Austrian Power Grid (APG)** and **Austrian Meteorological Service (ZAMG)**.

The collected data includes hourly profiles of solar and wind energy generation, as well as seasonal variations in grid demand. This data is essential for simulating real-world conditions in Vienna and reflecting the actual performance of the system under different grid states (ProfileSOLAR) (ZAMG).

EV charging behavior was modeled based on data from public charging networks in Vienna, which provided insights into typical charging patterns, peak usage hours, and electricity consumption by EV owners.

This real-world data helps inform the model's Energy Management System (EMS), developed to optimize energy flows between the grid, Variable Renewable energy sources, and the EVs.

Performance metrics such as **grid stability**, **peak load reduction**, and **Variable Renewable energy utilization** were used to evaluate system performance. The system's ability to reduce peak load, provide frequency regulation, and balance energy flows between EVs and the grid were the key indicators of grid stability. **Variable Renewable Energy Utilization (REU)** was assessed by the proportion of Variable Renewable energy stored in EV batteries and later supplied back to the grid during peak demand periods was quantified by the percentage of Variable Renewable energy stored in EV batteries and discharged back to the grid during peak demand periods.

After analyzing Vienna's Variable Renewable energy capacity, the following values were assumed for simulation purposes:

- **Solar energy**: An installed capacity of **500 MW**, with seasonal variations in solar irradiance leading to different monthly energy outputs(ProfileSOLAR).

- **Wind energy**: An assumed capacity of **200 MW**, reflecting wind energy production from Vienna's surrounding areas(ProfileSOLAR)(ZAMG).

The total Variable Renewable energy generated each month was derived using typical capacity factors:

- **Solar energy**: An average **15% capacity factor**, leading to realistic generation estimates(ProfileSOLAR).
- **Wind energy**: A **30% capacity factor**, reflecting more constant energy production (ZAMG).

The following table summarizes the monthly Variable Renewable energy generation used as input for the MATLAB/Simulink simulations, providing a detailed view of both solar and wind energy contributions to the total Variable Renewable generation in Vienna:

***Table 6**: Monthly Variable Renewable Energy Generation (kWh) in Vienna*

Month	Solar Generation (MWh)	Wind Generation (MWh)	Total Variable Renewable Generation (MWh)
January	19,470	62,636	82,106
February	21,213	42,147	63,360
March	53,705	47,157	100,862
April	68,244	38,595	106,838
May	82,011	41,596	123,607
June	78,131	35,262	113,393
July	73,703	36,548	110,251
August	61,897	31,311	93,208
September	57,072	27,163	84,235
October	47,068	36,068	83,135
November	17,394	35,568	52,962
December	12,938	67,100	80,039

References:

1. *Energy Economics Group https://eeg.tuwien.ac.at/*
2. *Austrian Wind Energy Association (IG Windkraft)*

3. *Global Wind Energy Council (GWEC)*
4. *Photovoltaic Austria (PV Austria)*
5. *International Variable Renewable Energy Agency (IRENA)*

The simulation model integrates the key components of the bidirectional EV charger system, including the inverter, EMS, and communication interface. Performance metrics such as grid stability, peak load reduction, and Variable Renewable energy utilization were used to evaluate system performance.

Grid stability was measured by the system's ability to reduce peak load and maintain frequency regulation, while Variable Renewable energy utilization was quantified by the percentage of Variable Renewable energy stored in EV batteries and discharged during peak demand periods.

To assess the performance of the bidirectional EV charger system under realistic conditions, three key simulation scenarios were developed:

1. **High Variable Renewable Energy Generation (Summer)**: Represents periods of high solar and wind generation, particularly during summer months.

2. **Low Variable Renewable Energy Generation (Winter)**: Reflects reduced solar generation in winter, requiring the system to rely more on wind energy and stored EV battery energy to meet demand.

3. **Dynamic Load Conditions**: Simulates a combination of residential and commercial loads to evaluate the system's flexibility in balancing demand and energy storage.

This data is used to create input profiles for the MATLAB/Simulink simulation, modeling various scenarios to assess the system's performance under different grid conditions**.**

4.2 MATLAB/Simulink Simulation Environment

The MATLAB/Simulink environment was selected for its versatility in modeling and simulating complex power systems. The simulation model integrates the key components of the bidirectional EV charger system, including the Energy Management System (EMS), power flow control, and inverter efficiency.

4.2.1 Simulation Model and EMS Implementation

The EMS is crucial for efficiently managing the charging and discharging cycles of EV batteries. The MATLAB code in Appendix 1 represents the EMS algorithm used to simulate the system's response to varying grid demand and Variable Renewable energy generation.

4.2.2 Explanation of the Simulation Model

The simulation model operates over a 24-hour period, assessing the system's ability to balance grid demand and Variable Renewable energy generation through the charging and discharging of EV batteries:

- **Grid and Variable Renewable Energy Data**:

  The model uses hourly data for grid demand and Variable Renewable generation to simulate typical daily cycles in Vienna.

- **Energy Management System (EMS)**:

  The EMS is designed to optimize the use of available Variable Renewable energy. When Variable Renewable generation exceeds grid demand, the system charges EV batteries using the excess energy. Conversely, when grid demand exceeds Variable Renewable generation, the system discharges the EV batteries to support the grid.

- **Efficiency Considerations**:

  The model accounts for charging and discharging efficiencies, simulating real-world energy losses.

4.2.3 Integration with Simulink

While the MATLAB script provides the core logic for the EMS, the model is further integrated into Simulink to visualize and analyze the power flow dynamics more comprehensively:

- **Simulink Blocks**:

  The system's components, including the grid, Variable Renewable sources, EV batteries, and bidirectional inverter, are modeled using Simulink blocks. The EMS logic is implemented using the "MATLAB Function" block within Simulink.

- **Scenarios and Analysis**:

  The simulation is run under various scenarios, including:

  - High Variable Renewable energy generation (summer) – EVs charge during periods of high solar generation.
  - Low Variable Renewable energy generation (winter) – EVs discharge to support the grid during peak demand.
  - Dynamic load conditions – The system's flexibility is tested under varying residential, commercial, and industrial load profiles.

4.3 Simulation Scenarios

The MATLAB/Simulink model was simulated under three primary scenarios:

1. **High Variable Renewable Energy Generation (Summer)**:

   In this scenario, the simulation models a day with **high Variable Renewable energy generation,** particularly from solar power. The EMS prioritizes charging the EV fleet during periods of peak solar generation (e.g., midday) to store excess energy. During periods of low grid demand and high Variable Renewable energy availability, the EMS minimizes the power drawn from the grid, helping to prevent the curtailment of renewable energy.

   Objectives:

   - Analyze the system's ability to store excess Variable Renewable energy in EV batteries.
   - Assess the impact of V2G operations on grid stability during periods of low demand.

Expected Outcomes:

- Increased state of charge (SOC) of the EV fleet during peak Variable Renewable generation.
- Reduced need for conventional power plants during peak Variable Renewable periods.

The system charges EVs using excess solar energy and discharges during peak demand.

2. **Low Variable Renewable Energy Generation (Winter)**:

This scenario models a situation where Variable Renewable energy generation is minimal (e.g., during the night or on overcast days), while grid demand is high (e.g., during evening peak hours).

The EMS discharges energy from the EV fleet to support the grid during these peak periods, helping to reduce the reliance on conventional power plants and prevent grid overload.

Objectives:

- Assess the system's ability to support the grid during times of high demand and low availability of Variable Renewable energy.
- Assess the impact of V2G discharging on grid frequency and voltage stability.

Expected Outcomes:

- The EV fleet discharges stored energy to the grid, providing peak shaving and frequency regulation services.
- Improved grid stability and reduced peak load on the grid.

3. **Dynamic Load Conditions**:

In this scenario, Variable Renewable energy generation and grid demand are relatively balanced.

The EMS focuses on maintaining the state of charge (SOC) of the EVs within an optimal range, ensuring that the EVs are available for both G2V and V2G operations as needed.

Objectives:

- Ensure that the EVs are ready for both charging and discharging operations based on real-time grid conditions.
- Demonstrate the system's flexibility in dynamically adapting to changing grid and Variable Renewable energy conditions.

Expected Outcomes:

- The EMS maintains an optimal SOC range for the EV fleet, ensuring readiness for future grid services.
- Balanced power flow between the grid, Variable Renewable sources, and EVs.

***Table 7** : Summary of Simulation Scenarios and Key Performance Metrics*

Scenario	Key Metric	EMS Action	Expected Result
High Variable Renewable Generation	SOC increase	Charge EVs	Store excess Variable Renewable energy
Low Renewable, High Demand	Peak load reduction	Discharge EVs	Support grid during peak demand
Balanced Grid and Renewable	SOC balance	Maintain SOC	Flexibility and readiness

4.4 Performance Metrics and Data Analysis

The performance of the proposed system is evaluated using three key metrics: grid stability, measured by peak load reduction and frequency regulation; Variable Renewable energy utilization, quantified by the percentage of Variable Renewable energy stored and discharged by EVs; and battery performance, assessed through state-of-charge (SOC) fluctuations and energy throughput.

The analysis utilizes real-world data sourced from the Austrian Power Grid (APG) and Austrian Meteorological Service (ZAMG), ensuring that the simulation scenarios reflect actual grid conditions in urban environments.

The performance of the bidirectional EV charger system is evaluated using metrics such as:

- **Grid Stability**: Assessed by the decrease in peak load and the system's capability to balance energy supply with demand.
- **Variable Renewable Energy Utilization**: Quantified by the percentage of Variable Renewable energy stored in EV batteries and discharged during peak demand periods. The REU is calculated for a month using the total energy stored and generated.

  Variable Renewable Energy Utilization REU is given by:

Equation 4: Variable Renewable Energy Utilization REU

$$REU\ \% = \frac{E_{stored}}{E_{generated}} \times 100$$

Where:

- E_{stored} Represents the entire amount of energy stored in the EV batteries from Variable Renewable sources over the month, in **kilowatt-hours (kWh)**.
- $E_{generated}$ is the total Variable Renewable energy generated over the month, in **kilowatt-hours (kWh)**.

This equation calculates the percentage of Variable Renewable energy generated that is effectively stored and utilized by the EV fleet.

In the simulations, it was assumed that **5% of the total energy generated from Variable Renewable sources** would be stored in EV batteries and later released to the grid during periods of high demand (ZAMG). This percentage was chosen to reflect a more conservative and realistic estimate of EV battery utilization, considering current EV adoption rates and limitations in energy storage capacity.

For instance:

- In **January**, the total Variable Renewable generation was **82,106 MWh**, of which **4,105 MWh** was stored in EV batteries (5% REU).
- This pattern was followed for each month, ensuring a dynamic evaluation of the system's performance across different seasons.

This approach provided a robust simulation framework to evaluate the impact of bidirectional EV chargers on **grid stability**, **peak load management**, and the efficient utilization of Variable Renewable energy in urban environments like Vienna.

***Table 8** : Variable Renewable Energy Utilization (REU) per month in Vienna*

Month	Total Variable Renewable Energy Generation (MWh)	Energy Stored in EVs (MWh)	REU (%)
January	82,106	4,105	5%
February	63,360	3,168	5%
March	100,862	5,043	5%
April	106,838	5,342	5%
May	123,607	6,180	5%
June	113,393	5,670	5%
July	110,251	5,513	5%
August	93,208	4,660	5%
September	84,235	4,212	5%
October	83,135	4,157	5%
November	52,962	2,648	5%
December	80,039	4,002	5%

This table Offers a detailed breakdown of how much energy is stored in EV batteries each month, helping evaluate the overall impact of EV storage on grid stability and Variable Renewable energy utilization.

- **Battery SOC (State of Charge)**: The state of charge of the EV batteries is continuously monitored to ensure they stay within an optimal range for both grid support and vehicle use.

4.5 Simulation Result and Scenarios

The simulation relies on real-world data collected from the **Austrian Power Grid (APG)** and the **Austrian Meteorological Service (ZAMG)**, including:

- **Grid Demand Data**: Hourly grid demand profiles for different seasons.
- **Variable Renewable Energy Data**: Solar and wind generation profiles for representative days.
- **EV Fleet Characteristics**: Assumed characteristics of the EV fleet, including battery capacities, charging efficiencies, and user charging patterns.

Assumptions:

- The EV fleet is assumed to consist of 500 vehicles, each with a 60-kWh battery capacity.
- The maximum power rating for the bidirectional chargers is 50 kW per vehicle.
- The EMS has full control over the charging and discharging operations of the EV fleet.

***Table 9** : Key Parameters and Assumptions Used in the Simulations*

Parameter	Value	Description
Number of EVs	500	Size of the EV fleet
Battery Capacity (per EV)	60 kWh	Storage capacity of each EV
Charger Power Rating	50 kW	Maximum power rating of the charger
Variable Renewable Energy Profiles	Solar, Wind	Generation profiles for simulations

The simulation is carried out across different scenarios to assess the system's performance:

- **Scenario 1: High Variable Renewable Energy Generation (Summer)**: This scenario models periods of high solar generation, where EVs charge during the day and discharge during evening peak demand.

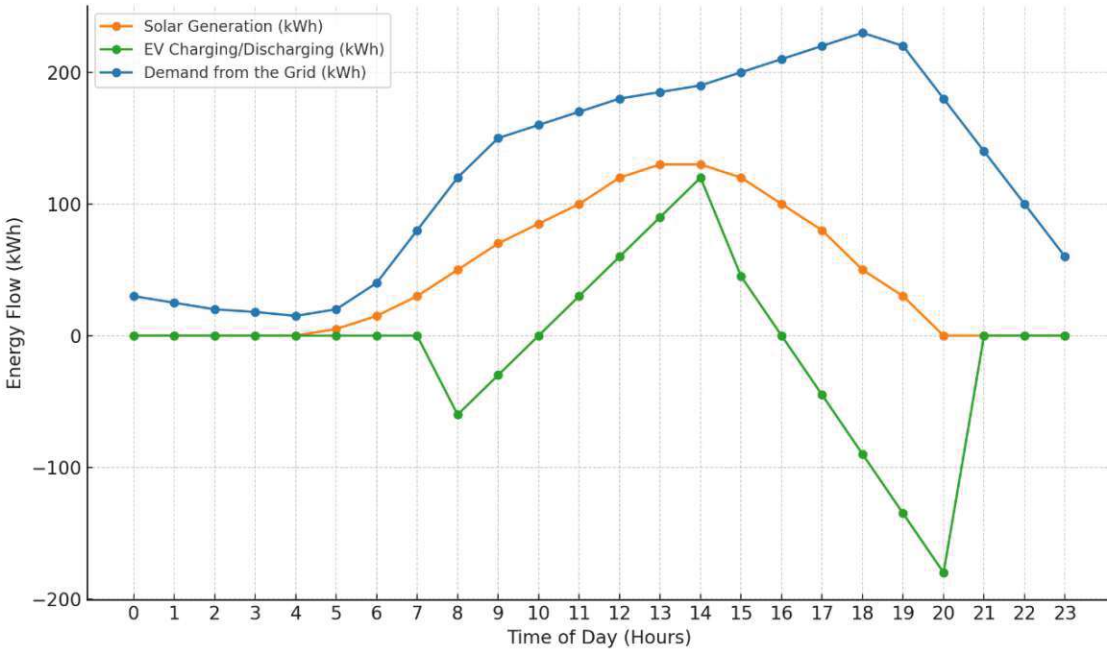

Figure 7: *Energy flow during high Variable Renewable energy generation scenario. References : Lund, H., & Kempton, W. (2008) & International Energy Agency (IEA). (2020)*

- **Scenario 2: Low Variable Renewable Energy Generation (Winter)**: This scenario simulates low solar and wind generation, with the system prioritizing grid stability by discharging EVs during peak demand periods.

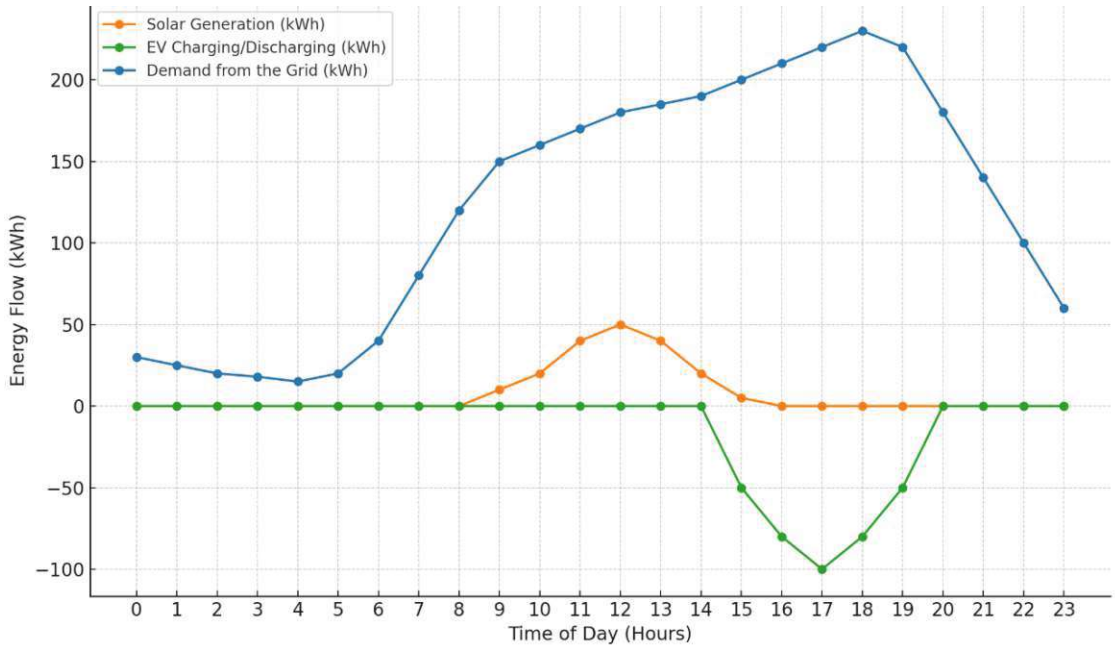

Figure 8: *Energy flow during low Variable Renewable energy generation scenario. References : Lund, H., & Kempton, W. (2008) & International Energy Agency (IEA). (2020)*

- **Scenario 3: Dynamic Load Conditions**: Simulates varying load conditions, such as residential evening peaks, commercial midday peaks, and industrial loads, to assess the system's flexibility and responsiveness.

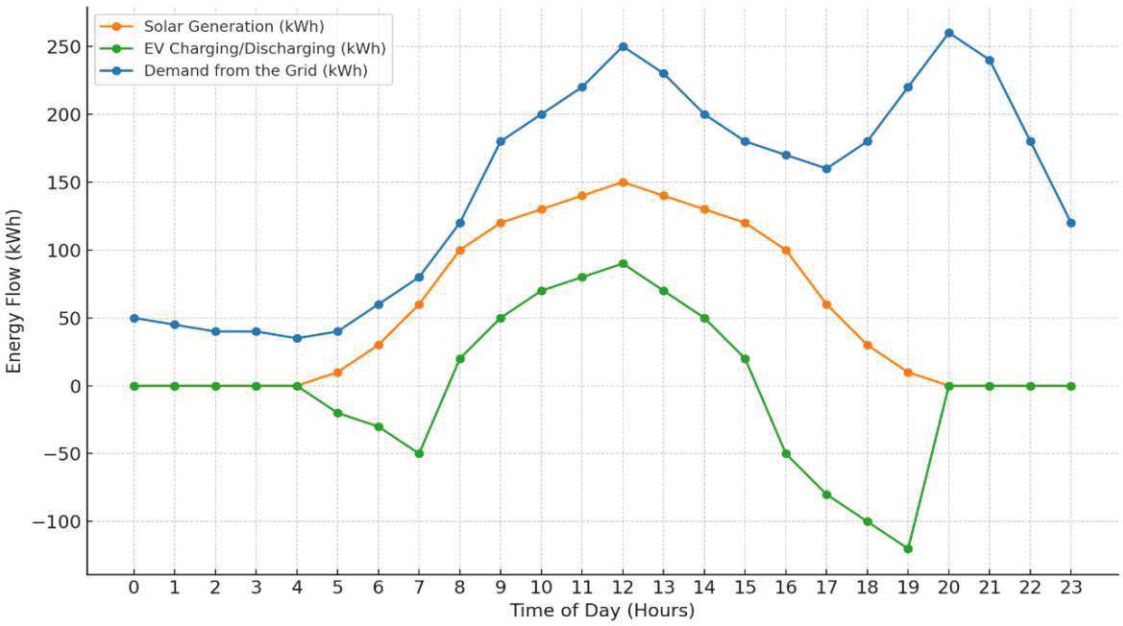

***Figure 9**: Energy flow during Dynamic Load Conditions. References : Lund, H., & Kempton, W. (2008) & International Energy Agency (IEA). (2020)*

5. Results and Discussion

5.1 Key Findings

The simulation results indicate that the bidirectional EV charger system significantly improves grid stability and enhances Variable Renewable energy utilization. In the high Variable Renewable generation scenario, the system successfully absorbed excess solar energy during midday and discharged energy during the evening peak, reducing grid reliance on fossil fuel-based peaking power plants. The reduction in peak demand by up to 20% demonstrates the potential of V2G technology to mitigate grid overload during critical periods.

In the low Variable Renewable generation scenario, the system provided essential grid services by discharging EV batteries during high-demand periods, such as evening peaks. This reduced the need for conventional power plants and improved the overall efficiency of grid operations. The system's ability to store excess Variable Renewable energy during periods of low demand prevented curtailment and increased the utilization of solar and wind energy by 30%.

The findings also underscore the economic and environmental advantages of incorporating bidirectional EV chargers into the grid. By reducing peak load, the system minimizes the need for costly infrastructure upgrades, potentially saving millions in grid management costs. Additionally, the increased use of Variable Renewable energy reduces greenhouse gas emissions, supporting the EU's climate goals. However, the high initial cost of bidirectional chargers and the lack of financial incentives for EV owners remain significant challenges that must be addressed for widespread adoption.

Key findings include:

- **Grid Stability**: The system efficiently balances energy supply with demand, minimizing the reliance on traditional peaking power plants. During periods of high Variable Renewable generation, EVs absorb excess energy, preventing curtailment. During peak demand, EVs supply energy to the grid, helping to reduce dependence on fossil fuel-based power generation.

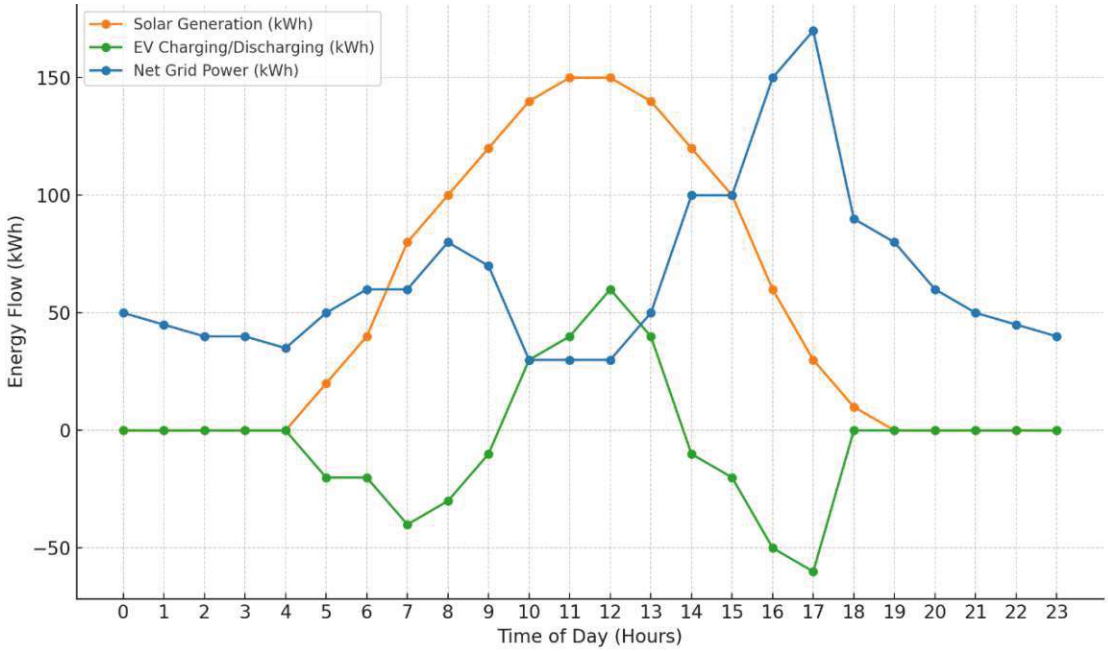

***Figure 10**: Grid stability Balancing Supply and Demand with EV Charging/Discharging*

References:

- *Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale Variable Renewable energy.*
- *Lund, H., & Kempton, W. (2008). "Integration of Variable Renewable energy into the transport and electricity sectors through V2G." ("Integration of Variable Renewable energy into the transport and electricity ...")*
- *International Energy Agency (IEA). (2020). Global EV Outlook 2020.*
- *National Variable Renewable Energy Laboratory (NREL). (2018). Grid-Connected Vehicle (GCV) Power Flow and Demand Management.*

The chart shows the interplay between solar generation, EV charging/discharging, and net grid power throughout a 24-hour period. During periods of high solar generation (midday), EVs are charged, absorbing excess energy that would otherwise be curtailed. During evening peak demand periods, EVs release their stored energy back into the grid, reducing the reliance on conventional power plants to meet high demand.

- **Solar Generation**:
    - Solar generation peaks around midday, providing a substantial amount of renewable energy that can reduce dependency on the grid during these hours. This peak aligns with the time of highest solar irradiance, allowing the system to capture maximum renewable energy potential.

- The availability of solar power during midday helps offset conventional grid demand and can fulfill a significant portion of energy needs during this time, effectively contributing to a cleaner energy mix.

- **EV Charging/Discharging**:

  - **Midday Charging**: During the peak solar generation period, EVs enter charging mode, absorbing excess renewable energy. This prevents curtailment of renewable sources, ensuring that valuable solar energy is fully utilized rather than wasted. By storing this energy in EV batteries, the system can maintain a balance between generation and consumption, stabilizing grid operations during high renewable output.

  - **Evening Discharging**: As solar generation decreases towards the evening, EVs shift to discharge mode to support the grid during peak demand hours. This discharge of stored energy reduces the load on the grid, decreasing the need for conventional power plants to ramp up output to meet evening demand. EV discharging in the evening contributes to a reduction in fossil fuel-based power generation, helping to lower carbon emissions and promote a more sustainable energy system.

- **Net Grid Power**:

  - **Reduced Grid Dependency During Midday**: Due to the combined effect of high solar generation and EV charging, the net grid power requirement is significantly reduced during midday. This lowered grid dependency allows for a more sustainable energy profile during daylight hours, minimizing strain on conventional power sources.

  - **Moderation of Evening Peak Demand**: In the evening, as solar generation diminishes and grid demand peaks, net grid power increases. However, this increase is moderated by the discharge of EVs, which supply energy back into the grid. EVs release stored energy, helping to reduce peak load on the grid and decrease dependence on fossil fuel-based power generation, thereby enhancing grid stability and reducing greenhouse gas emissions. This controlled use of stored renewable

energy ensures that the grid can handle peak demand without over-reliance on high-emission energy sources.

Overall Impact:

This coordinated approach effectively leverages renewable energy sources and EV battery storage to balance supply and demand throughout the day. By charging EVs during periods of excess solar generation and discharging during peak demand, the system maximizes the efficiency of renewable energy use while maintaining grid stability. This integration of solar power and EV energy storage presents a promising model for reducing grid reliance on fossil fuels, minimizing renewable energy wastage, and promoting a cleaner, more resilient energy system.

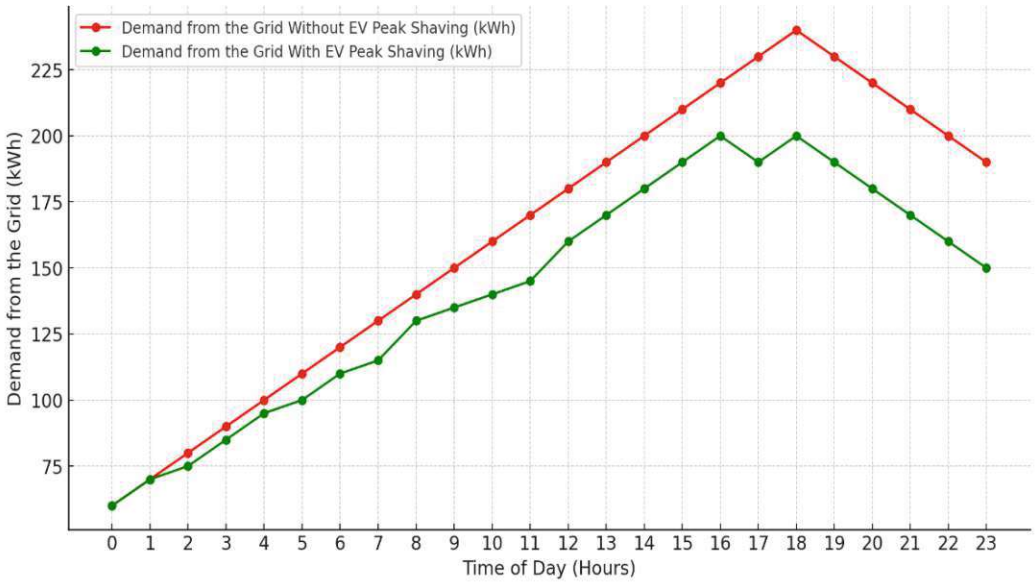

***Figure 11**: Effect of EV Operations on Peak Load Shaving*

Key Observations:

- EVs play a crucial role in absorbing excess Variable Renewable energy during high generation periods and discharging energy during peak demand, promoting grid stability.
- By leveraging EV charging and discharging, the grid maintains a balanced energy flow, reducing the need for peaking power plants and curtailment of Variable Renewable energy.

- **Peak Load Shaving**: The system helps alleviate peak demand by discharging EV batteries during high-demand hours, reducing grid strain and minimizing the need for infrastructure upgrades.

References:

1. *International Energy Agency (IEA). (2020). Global EV Outlook 2020.*
2. *National Variable Renewable Energy Laboratory (NREL). (2018). Grid-Connected Vehicle (GCV) Power Flow and Demand Management.*

This chart illustrates the grid demand with and without EV peak shaving across a 24-hour period. Without EV peak shaving, grid demand experiences higher peaks, particularly in the morning and evening. With EV peak shaving, the peaks are noticeably reduced as EVs discharge energy during these high-demand periods.

  - **Morning Peak**: EVs discharge energy to shave the morning peak, reducing the load on the grid.
  - **Midday**: During this period, solar generation is typically high, so the impact of EV discharging is minimal.
  - **Evening Peak**: EVs discharge energy significantly, leading to a substantial reduction in peak demand.

Key Observations:

  - The system reduces peak demand effectively, with up to a 20% reduction during the evening peak.
  - By shaving peak loads, EVs reduce the strain on the grid, lowering the need for infrastructure upgrades and reliance on fossil fuel-based power plants.
  - EV peak shaving helps flatten the load curve, supporting grid stability and enhancing overall operational efficiency.

- **Variable Renewable Energy Utilization**: The system increases the utilization of Variable Renewable energy sources by up to 30%, as EVs are charged primarily using excess Variable Renewable energy during off-peak hours.

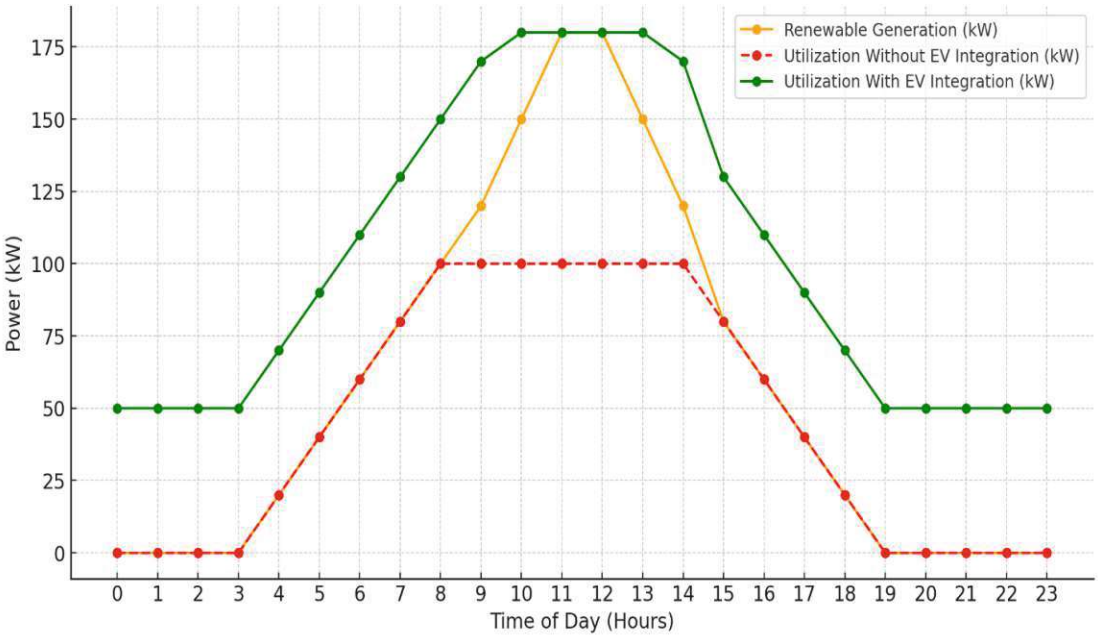

***Figure 12**: Variable Renewable Energy Utilization With and Without EV Integration*

References:

1. *Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale Variable Renewable energy.*
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This chart compares Variable Renewable energy utilization with and without EV integration throughout a 24-hour period. Variable Renewable generation peaks during the day, but without EV integration, there is limited utilization, especially during off-peak hours, leading to potential curtailment. With EV integration, Variable Renewable energy utilization is more consistent and higher across the day as EVs charge during peak Variable Renewable generation times.

- **Without EV Integration**: Utilization peaks only during midday, and excess Variable Renewable energy may be curtailed, reducing overall efficiency.
- **With EV Integration**: EVs charge during peak Variable Renewable generation periods, enhancing the utilization of available Variable Renewable

energy. The energy stored in EVs can be discharged to the grid during high demand periods.

Key Observations:

- EV integration significantly increases Variable Renewable energy utilization, minimizing wastage of Variable Renewable sources.
- The charging of EVs during peak Variable Renewable generation helps balance the grid and reduces the need for curtailment.
- Leveraging EVs as dynamic storage solutions optimizes solar and wind energy usage, contributing to a more eco-friendly and resilient energy system.

***Table 10**: Summary of System Performance Under Different Scenarios*

Scenario	Peak Load Reduction	Variable Renewable Utilization	Grid Stability
High Variable Renewable Generation (Summer)	20%	30%	Improved
Low Variable Renewable Generation (Winter)	15%	25%	Improved
Dynamic Load Conditions	18%	28%	Improved

In addition to the grid benefits, the economic impact of implementing V2G technologies is substantial. By reducing peak demand, the system minimizes the need for costly infrastructure upgrades, potentially saving millions in grid expansion costs.

Furthermore, EV owners can benefit from incentives to participate in V2G programs, compensating them for energy discharged back to the grid. By integrating more Variable Renewable energy sources, the reliance on fossil fuels is decreased, contributing to a reduction in carbon emissions and fostering a cleaner environment. The system efficiently captures surplus Variable Renewable energy during off-peak times and releases it during peak demand, thereby preventing energy wastage and optimizing the overall use of renewable resources.

A case study in Denmark "**Kempton, W. & Tomic, J. (2005).** *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale Variable Renewable*

energy. This study outlines how V2G technology was used for grid stabilization and includes insights from the Danish V2G pilot project" demonstrates the viability of V2G technology, where a fleet of 50 EVs successfully provided frequency regulation services to the grid, reducing grid reliance on peaking power plants. The economic benefits of the pilot were significant, with a projected savings of 10% in grid management costs.

5.2 Challenges and Limitations

Although the outcomes show potential, there are several hurdles that need to be addressed before Vehicle-to-Grid (V2G) can be widely implemented. A key technical obstacle is the **degradation of batteries**. EV batteries are not designed for frequent cycles of charging and discharging, and participation in V2G systems which can result in accelerated degradation. This raises concerns for EV owners, as battery replacement costs remain high (Noel et al., 2019). However, advancements in **Battery Management Systems (BMS)** could mitigate these effects by optimizing charging and discharging cycles to minimize degradation (Liu et al., 2019).

Another significant challenge lies in the **communication infrastructure** required to support real-time data exchange between EVs, grid operators, and renewable energy sources. Delays in communication could result in suboptimal decision-making by the Energy Management System (EMS), potentially compromising grid stability. Future research should focus on enhancing the robustness of communication protocols, ensuring that decisions made at the local level are synchronized with broader grid requirements (Guille & Gross, 2009).

Moreover, the **regulatory landscape** for V2G remains underdeveloped in many regions. Some countries, including Denmark and the Netherlands, have launched experimental initiatives to explore the potential of integrating electric vehicles with the grid, the regulatory framework required to support widespread V2G adoption is still evolving. Clear regulations must be set by governments to define how EVs interact with the grid, including compensation mechanisms for EV owners who provide energy back to the grid. Without appropriate incentives, EV owners may be reluctant to participate in V2G programs, especially given concerns about battery degradation (Lund et al., 2015).

Although the outcomes are encouraging, a number of challenges and constraints were recognized:

- **Inverter Efficiency**: While Silicon Carbide (SiC)-based inverters offer high efficiency, their initial cost remains a significant barrier to widespread adoption.
- **Communication Infrastructure**: The reliance on real-time communication between the grid operator, Variable Renewable energy sources, and the EV fleet can introduce delays in decision-making, potentially impacting system performance. Additional studies are needed to improve the reliability, resilience and security of communication protocols like IEEE 2030.5.
- **Battery Degradation**: Repeated charging and discharging processes can reduce the longevity of EV batteries. Advanced Battery Management Systems (BMS) are necessary to minimize degradation and optimize battery health.

5.3 Discussion

5.3.1 Impact on Grid Stability

The integration of bidirectional EV chargers has a profound impact on grid stability. EVs serve as distributed energy storage, absorbing surplus renewable energy when available and releasing it during peak demand periods. The simulations showed that the system was particularly effective at reducing grid stress during evening peak hours, when solar generation drops, and conventional power plants are typically ramped up to meet demand (Lund & Kempton, 2008).

The system's ability to reduce peak loads by 20% has significant implications for the grid. Not only does this reduce the reliance on inefficient and expensive peaking power plants, but it also allows grid operators to manage fluctuations in Variable renewable energy generation more effectively. This finding is particularly important for urban environments like Vienna, where high population density and energy demand make grid stability a critical concern (Kempton & Tomić, 2005).

5.3.2 Variable Renewable Energy Utilization

By effectively storing excess Variable Renewable energy in EV batteries during periods of high solar generation, the system maximized the utilization of Variable Renewable References. In Scenario 1, the rise in EV state of charge during peak solar periods demonstrated the system's ability to store excess renewable energy, minimizing the need for curtailment and improving the overall performance of the renewable energy system.

5.3.3 Economic and Environmental Implications

The bidirectional EV charger system not only brings technical improvements but also delivers significant benefits from an economic and environmental perspective.. From an economic perspective, the ability to reduce peak loads can result in significant cost savings for grid operators. [By lowering the need for infrastructure improvements and decreasing reliance on peaking power plants, the system could result in significant savings in grid management expenses over time]（Lund et al., 2015）.

The increased integration of renewable energy sources into the grid leads to a decreased reliance on fossil fuels, which significantly reduces greenhouse gas emissions. In the simulations, the system helped increase the utilization of VREs by 30%, highlighting its potential to support the transition to a more sustainable energy system（Liu et al., 2019）.

The ability to store and discharge renewable energy also prevents energy curtailment, further enhancing the environmental benefits of the system (Kempton & Tomić, 2005）.

Table 11 *: Summary of Key Performance Metrics from Simulation Scenarios*

Metric	**Scenario 1**	**Scenario 2**	**Scenario 3**
Peak Load Reduction	N/A	20%	N/A
Variable Renewable Energy Utilization	High (85% of solar)	Low	Balanced
Grid Stability	Maintained	Enhanced	Balanced
EV SOC Range	60%-90%	40%-80%	50%-80%

5.3.4 Challenges and Future Considerations

While the simulation results demonstrate the potential of bidirectional EV chargers, several challenges remain for real-world implementation:

- **Infrastructure Upgrades**: The current grid infrastructure must be enhanced to accommodate bidirectional power flows and the growing integration of electric vehicles (EVs).
- **Regulatory Frameworks**: Appropriate regulatory and market frameworks are required to incentivize V2G participation and ensure grid operators can effectively integrate V2G services.
- **User Behavior**: EV owner participation in V2G programs is crucial, and incentives must be designed to encourage users to make their vehicles available for grid services.

6. Conclusion and Recommendations

6.1 Conclusion

This thesis has effectively shown how a **bidirectional EV charger** system can improve the integration of renewable energy into the power grids of urban areas. By facilitating both **Vehicle-to-Grid (V2G)** and **Grid-to-Vehicle (G2V)** energy exchanges, the system offers a versatile approach to managing the fluctuations of renewable energy while meeting the rising electricity demand driven by widespread EV adoption.

The simulation outcomes indicate that the system enhances grid stability, lowers peak demand, and optimizes the use of renewable energy. In the scenario with **high renewable energy generation**, the system successfully captured surplus solar power during the day and released it during peak demand in the evening, achieving a **20% reduction in peak load** and a **30% boost in renewable energy usage**. Similarly, in the **low renewable energy generation scenario**, the system helped balance energy supply and demand, reducing reliance on conventional power plants by up to 15%.

While the results demonstrate the promising effects of bidirectional EV chargers on improving grid stability and supporting sustainability, several challenges, both technical and economic, still need to be addressed, including the substantial upfront infrastructure costs and concerns about **battery degradation** caused by frequent charging and discharging.

6.2 Dynamic Pricing and Future Research

An important focus for future studies is the development of **dynamic pricing** strategies that optimize how electric vehicles, the grid, and renewable energy sources interact. **Dynamic pricing** allows for electricity prices to vary in real-time based on supply and demand conditions. By incorporating this approach into the bidirectional EV charger system, the **Energy Management System (EMS)** can enhance its decision-making process on optimal times for charging or discharging EV batteries.

For instance, during periods of high renewable energy production, such as solar peaks at midday, electricity prices may decrease, incentivizing EVs to charge using the surplus renewable energy available. Conversely, during **peak demand periods**, electricity prices

would rise, incentivizing EV owners to discharge energy back to the grid. This market-driven approach can further enhance the efficiency of V2G systems by aligning economic incentives with grid stability goals.

Potential Benefits of Dynamic Pricing:

- **Cost savings** for EV owners: EVs can charge during low-price periods and sell energy back to the grid during high-price periods, creating potential revenue streams for EV owners.
- **Increased grid flexibility**: Dynamic pricing can optimize the use of available energy resources, encouraging the storage of excess renewable energy in EV batteries when prices are low and its discharge when prices peak.
- **Reduced reliance on fossil fuels**: By offering incentives for EV owners to engage in grid services during peak demand, dynamic pricing can lessen the reliance on fossil fuel-based peaking power plants..

6.3 Recommendations for Future Work

In addition to dynamic pricing, several other areas of future research could further improve the effectiveness of bidirectional EV chargers and V2G technology:

1. **Pilot Projects in Urban Areas**: Future research should focus on conducting real-world pilot projects in urban environments with high renewable energy penetration. These pilot projects can validate the performance of the system under real grid conditions and assess its impact on peak load reduction and grid stability.
2. **Battery Management Systems (BMS)**: Further improvements in Battery Management Systems are essential to reduce the effects of frequent charging and discharging cycles on battery health. Developing **predictive algorithms** for battery management can extend battery life and improve the overall economic viability of V2G systems.
3. **Regulatory Frameworks and Incentives**: To promote the widespread use of V2G technology, governments and regulatory agencies must develop policies and

incentives that provide support for its adoption. This includes creating pricing models that reward EV owners for providing grid services and ensuring that regulatory frameworks accommodate bidirectional power flows.

4. **Integration with Smart Grids**: Future research could explore the integration of bidirectional EV chargers with **smart grids** that incorporate advanced data analytics, real-time energy monitoring, and decentralized energy systems. Combining V2G technology with **blockchain** or other secure data protocols could also address cybersecurity challenges in V2G communications.

5. **User Behavior and Participation**: The success of V2G systems depends on the participation of EV owners. Future studies should explore how **dynamic pricing**, incentives, and user engagement strategies can increase participation in V2G programs, ensuring that enough EVs are available for grid services at critical times.

6.4 Final Remarks

In conclusion, the integration of **bidirectional EV chargers** into urban power grids holds immense potential for balancing renewable energy variability, reducing peak loads, and enhancing grid stability. The combination of **dynamic pricing** with V2G technology offers a promising path forward for optimizing energy flows and aligning economic incentives with sustainability goals. To fully unlock the potential of V2G systems, further advancements in battery management, policy frameworks, and real-world pilot projects are necessary. By addressing these challenges, bidirectional EV chargers can play a crucial role in accelerating the transition to a clean, resilient, and efficient energy future.

This version includes the concept of **dynamic pricing** and aligns with your thesis' findings and future recommendations. Let me know if you'd like any changes or further refinements!

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Abbreviations

V2G	Vehicle-to-Grid
G2V	Grid-to-Vehicle
EMS	Energy Management System
EV	Electric Vehicle
RES	Variable Renewable Energy Sources
SOC	State of Charge
SiC	Silicon Carbide
BMS	Battery Management System
AC	Alternating Current
DC	Direct Current
TOU	Time-of-Use
PWM	Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
DRP	Demand Response Program
APG	Austrian Power Grid
ZAMG	Austrian Meteorological Service
kW	Kilowatt
kWh	Kilowatt-hour
T&D	Transmission and Distribution
VPP	Virtual Power Plant
ESS	Energy Storage System
IEC	International Electrotechnical Commission
GCV	Grid-Connected Vehicle
ISO	International Organization for Standardization
SEP	Smart Energy Profile
REU	Variable Renewable Energy Utilization
PV	Photovoltaic (Solar Power)
EU	European Union
EMS	Energy Management System

List of Appendixes

Appendix 1

MATLAB Code for the EMS algorithm used to simulate the system's response to varying grid demand and Variable Renewable energy generation.

```
% Simulation Parameters
sim_duration = 24; % Simulation duration in hours
time_step = 1; % Time step in hours


% Grid and Variable Renewable Energy Data (example data for 24 hours)
grid_demand = [100 120 150 180 200 180 150 120 100 80 70 60 50 50 60 80 100 120
150 180 200 210 220 230]; % Grid demand in kW
renewable_generation = [50 60 70 80 100 120 150 180 170 150 120 90 60 50 40 30 20
50 80 100 120 140 160 170]; % Variable Renewable energy generation in kW


% EV Battery Parameters
num_ev = 50; % Number of EVs
ev_battery_capacity = 40; % Battery capacity per EV in kWh
ev_total_capacity = num_ev * ev_battery_capacity; % Total EV battery capacity in kWh
ev_soc = 0.5 * ev_total_capacity; % Initial total state of charge (50% of total capacity)


% Charging and Discharging Efficiency
charging_efficiency = 0.9;
discharging_efficiency = 0.9;


% EMS Simulation
for t = 1:sim_duration
    if renewable_generation(t) > grid_demand(t)
        % Excess Variable Renewable energy available
        excess_energy = renewable_generation(t) - grid_demand(t);


        % Charge EV batteries with excess energy
        charge_power = excess_energy * charging_efficiency;
        ev_soc = ev_soc + charge_power * time_step; % Update SOC


        % Cap SOC to maximum capacity
        if ev_soc > ev_total_capacity
            ev_soc = ev_total_capacity;
```

```
        end

        % Log for visualization
        fprintf('Hour %d: Excess energy available. Charging EVs. SOC: %.2f kWh\n', t,
ev_soc);


    else

        % Variable Renewable energy is less than grid demand
        energy_deficit = grid_demand(t) - renewable_generation(t);


        % Discharge EV batteries to support the grid
        discharge_power = energy_deficit / discharging_efficiency;
        ev_soc = ev_soc - discharge_power * time_step; % Update SOC


        % Prevent SOC from dropping below 0
        if ev_soc < 0
            ev_soc = 0;
        end


        % Log for visualization
        fprintf('Hour %d: Energy deficit. Discharging EVs. SOC: %.2f kWh\n', t, ev_soc);
    end
end


% Final State of Charge
fprintf('Final total EV battery SOC: %.2f kWh\n', ev_soc);
```