TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

THESIS NO:075/MSPSE/011

VEHICLE-TO-GRID ENABLED SMART GRID FOR LOAD LEVELLING AND COST ANALYSIS UNDER TOU TARIFF: CASE STUDY OF NEPAL’S BANESHWOR FEEDE

BY
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A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE IN POWER SYSTEM ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING
IOE, PULCHOWK CAMPUS
LALITPUR, NEPAL

JANUARY, 2026

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CERTIFICATE OF APPROVAL

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Date: January 2026

ACKNOWLEDGEMENT

I would like to express my heartfelt thanks to all those who have contributed to the successful completion of this thesis entitled *“Vehicle to Grid(V2G) Enabled Smart Grid for Load Levelling and Cost Analysis under TOU Tariff: Case Study of Nepal’s BaneshworFeeder”*. This journey has been both challenging and rewarding but made possible through the constant collaboration, guidance, and encouragement of several people and institutions.

First and foremost, I am grateful to Er. Anil Kumar Panjiyar, Assistant Professor, Department of Electrical Engineering, Pulchowk Campus, for his guidance from the early stages of this thesis and his patience and encouragement throughout this work. His expertise in power systems and thoughtful supervision has been instrumental in shaping this work to its present form.

I am also sincerely thankful to the Head of the Electrical Engineering Department and all the faculty members of the Institute of Engineering, Pulchowk Campus, for their advice, encouragement, and academic guidance during my studies. I wish to extend my appreciation to the technical staff, laboratory assistants, and my colleagues for their cooperation and assistance throughout this research period.

Special thanks are due to the Baneshwor Grid Operation Department and Baneshwor Distribution Control System (DCS) for their invaluable support in providing essential field data and technical information.

Furthermore, I gratefully acknowledge the Department of Mechanical Engineering, Kathmandu University, for hosting the *4th University Scholar Conference 2025: ENGINEERING, INNOVATION AND ADVANCEMENTS*, which offered valuable exposure and the opportunity to present and refine this research.

Finally, I am deeply thankful to my friends and family for their constant motivation, patience, and unwavering support. This thesis stands as a reflection of the collective effort and support of everyone mentioned above, and I am truly grateful for their contributions to my academic and personal growth

ABSTRACT

The mass adoption of electric vehicles (EVs) is fundamentally altering the pattern of electricity demand in electricity distribution networks. While EVs do add to cleaner transportation, uncoordinated charging may create a number of operational problems for distribution feeders, such as higher evening peaks, higher demand volatility, voltage deviations and lower overall network efficiency. These challenges are especially important in dense urban settings, where existing radial feeders did not necessarily account for large numbers of flexible EV loads.

This research focuses on the Vehicle-to-Grid (V2G) integration as a viable solution to load levelling and cost reduction in radial distribution systems. A coordinated V2G control framework is formulated and tested based on real operating data of the 11 kV Baneshwor radial feeder in Kathmandu, Nepal so that the analysis is based on actual load conditions and EV user behavior. The model incorporates key real-world constraints, such as individual plug-in and plug-out schedules, partial V2G participation and reserve state of charge (SOC) limits to protect battery health and assure driver mobility.

Simulation results show that coordinated V2G operation can be a very good approach to smooth the feeder load profile by shifting peak demand and filling demand valleys, and can improve the feeder performance and reduce operational stress. An economic analysis under a time-of-use (TOU) tariff shows that it is possible for EV owners participating in V2G to have lower daily net cost of charging, despite the simplified calculation of battery degradation cost. To check the generalizability of the approach, similar improvements are obtained for the framework applied to the IEEE-33 bus radial distribution system as well. Overall, the study concludes that integration of V2G can not only reinforce the grid operations but also provide direct financial benefits to the EV-owner, making it a promising and scalable strategy for smart grid planning in developing power systems such as Nepal's.

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LIST OF ABBREVIATIONS

V2G	VEHICLE TO GRID
TOU	TIME OF USE
EV	ELECTRIC VEHICLE
DSO	DISTRIBUTION SYSTEM OPERATOR
SOC	STATE OF CHARGE
PU	PER UNIT

CHAPTER 1: INTRODUCTION

1.1 Background

The global energy sector is experiencing a profound change, fueled by a growing pressure to minimize greenhouse emission, improve energy efficiency, and use cleaner and more sustainable ways of producing and utilizing electricity. This energy transition is not only about power generation but it's also about doing so in multiple sectors, and the electrification of transportation is one of the most prominent and impactful of all.

Electric vehicles (EVs) are now playing a key role in energy and mobility policies today. Compared with traditional internal combustion engine vehicles, EVs have many advantages, such as lower local air pollution, lower carbon emissions when running on clean electricity and higher energy conversion efficiency. For consumers, EVs usually mean operating and maintenance cost savings because they have less mechanical design and fewer moving parts. In the past decade, improvements in battery technology, falling battery costs, and strong policy support have led to a proliferation of EVs across the world. Consequently, electricity demand related to EV charging is quickly becoming an important and dynamic component of daily power system loads.

While the emergence of electric mobility contributes to the long term sustainability goals, it also presents new challenges for power networks in operation, especially at the distribution level. EV charging loads are unique from traditional electricity demand in that they are mobile, highly time dependent and driven by human travel behavior. Most of the EV owners drive during the day and charge their vehicles when they return home in the evening, which leads to synchronized charging patterns. If left unmanaged, this clustering of charging demand is often coincident with existing residential peaks, worsening feeder loading and increasing short term stress on distribution networks.

Distribution feeders and transformers have traditionally been based on historical load patterns on the premise of gradual and predictable load growth. In many urban areas, low and medium voltage networks are already operating close to their thermal and voltage limits during peak times. The addition of uncoordinated EV charging adds to operational problems, including peak load increases, voltage deviations, transformer loading, increased technical losses and accelerated equipment aging. Over time, these effects can result in reduced system efficiency and require costly infrastructure upgrade in advance of time expected by the utility.

From the consumer's point of view, uncontrolled charging can also result in higher electricity bills, as the charging during peak tariff periods can raise the cost of energy every day and damage the economic attractiveness of EV ownership. Thus, the difficulty lies both in the technical and economic aspects: integration of EV into the distribution networks must guarantee the reliability of the grid, while remaining cost effective to users. For these reasons, intelligent charging and advanced energy management strategies are increasingly identified as being essential to the successful large-scale integration of EVs.

1.1.1 Vehicle to Grid as a Smart EV- Grid Interaction Strategy

To solve the operational challenges of uncoordinated charging of EVs, Vehicle to Grid (V2G) technology has emerged as a practical and widely recognized solution for the smarter interaction of EV grid. V2G opens up the two-way power flow between the EV battery and the power grid so that the EVs can not only consume the power from the grid but also can act as distributed energy storage resources for the grid, actively supporting the grid operation if properly managed. Within a V2G framework, EVs are expected to be kept charging in periods of low demand or low electricity price and can reverse the stored energy out to the grid during periods of high demand. This operational flexibility turns EVs from passive loads to active demand side management participants. Through the coordinated control strategies, aggregated EV fleets can offer valuable services such as peak shaving, valley filling, and load balancing at the feeder level which is especially beneficial in urban distribution systems with significant peaks and limited flexibility. If properly coordinated, V2G can help to improve feeder load profiles by taking sharp peaks and redistributing demand throughout the day. This generally improves the load factor and also allows existing infrastructure to work at closer to ideal utilisation. In practice, this means less stress on transformers and feeder conductors, less voltage fluctuation and a better overall system stability. These benefits can postpone the necessity for expensive network reinforcement and further to mitigate the operational problems related to large scale EV adoption.V2G integration also offers major economic opportunities to EV owners. Under time of use (TOU) tariffs users can strategically reduce their cost of charging by scheduling their charging time during off-peak hours when electricity rates are lowest.

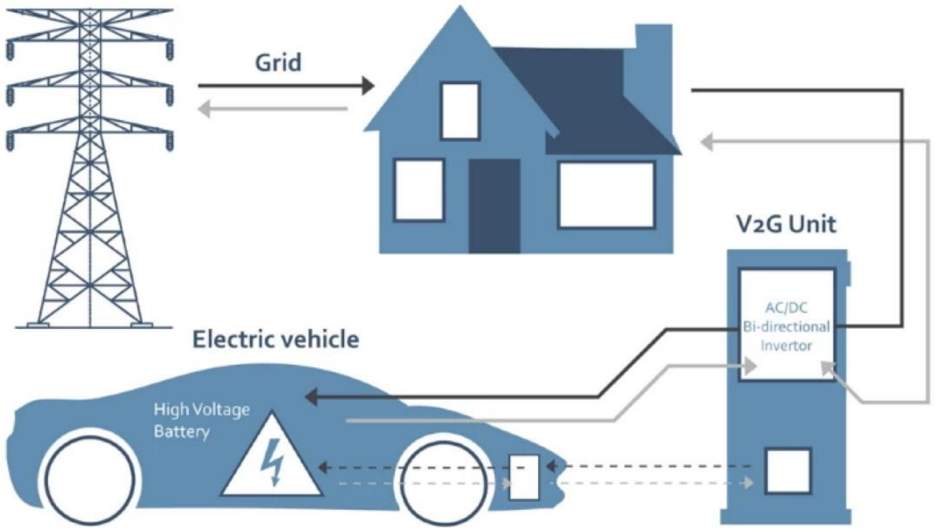

Figure 1: Schematic Diagram of Vehicle to Grid System Operation

Additionally, EV owners may be offered revenue or credits for discharging stored energy back to the grid during periods of high electricity prices, offering a direct financial incentive for participation. When the compensation mechanisms are properly structured and charging/discharging cycles are dealt with through solid battery protection measures, the accumulated economic benefits can be greater than the incremental costs associated with battery wear and round trip efficiency losses. Therefore, V2G provides a win-win situation, which provides flexibility and stability to the grid, while at the same time offering the tangible financial benefits to the participating EV owners.

1.1.2 V2G and Renewable Energy Integration

In addition to helping to improve daily feeder load profiles, V2G plays a critical role in helping support renewable energy integration. Sources such as solar and wind are naturally intermittent, with their output being rapidly varying, dependent on changing weather and environmental conditions. This variability presents a tremendous challenge for maintaining a real time balance between supply and demand, especially as the percentage of renewables in the generation mix is increasing. Aggregated and coordinated EV batteries can feed this excess renewable generation into batteries as flexibility during periods of high renewable generation with low demand, and release stored energy during periods of low renewable generation or high system demand. In this distributed storage role, EV fleets contribute to overall system resilience, fossil fuel independence of peak generation plants, and help address the operational challenges associated with the integration of variable renewables. As the power systems move more towards higher proportions of renewables, V2G is becoming a useful tool for improving the flexibility of the grid, helping to support stable operations, and allowing for a cleaner energy future.

1.1.3 Practical Challenges of Implementing V2G

Despite its promise, the implementation of V2G is a complex, multifaceted challenge. Successful V2G deployment requires strong, real-time communication between EVs, charging stations, aggregators and the grid. Furthermore, more sophisticated control algorithms are required to coordinate the charging and discharging schedules, so that network constraints and user preferences are always respected. A critical complication is the inescapable uncertainty in the availability of EVs, which is determined by the varying and changing patterns of travel by users. Moreover, V2G participation is likely to be partial in the real world as many EV owners may choose not to participate in discharging because of concerns related to the health of their battery pack, their personal mobility needs, or insufficient incentives. Battery degradation is considered the key issue for users and system planners. If charging and discharging cycles are not carefully optimized, too many cycles of charging and discharging can cause batteries to deteriorate more quickly and lower the overall battery life. Accordingly, the realistic modeling of V2G requires enforcing strict battery protection constraints such as minimum state of charge (SOC), reserved SOC for guaranteed mobility as well as mandatory target SOC at departure times. It is equally important to accurately model partial participation, which is more representative of real decisions and behaviors of EV owners and in contrast to the realistically often-unrealistic assumption of universal V2G engagement. Collectively, these factors highlight the need for realistic V2G modelling frameworks that integrate real system constraints, operational uncertainties and various user behaviors. Such models are imperative in producing relevant and transferable results more so than idealized or overly optimistic assumptions.

1.1.4 Nepal Context and Motivation for This Study

In developing countries like Nepal, there are both significant challenges and potential opportunities for the integration of electric vehicles (EVs). Nepal's power sector is experiencing fast growth in urban electricity demand and an increased interest in electric mobility, while facing a lack of flexibility in its existing electricity distribution infrastructure. Metropolitan areas such as the Kathmandu Valley already have significant variability of load and evening peaks of demand. Distribution feeders, such as that of Baneshwor (11 kV), commonly run near their capacity limits even during peak hours, without adding EV charging loads. Introducing uncoordinated EV charging to these feeders can seriously increase the risk of overloading, make voltage fluctuations worse, and put stress on network assets. On the other hand, as Nepal is gradually progressing toward electric mobility, it presents an ideal opportunity to implement advanced grid management and demand side strategies at an early stage before large-scale adoption of EVs. Proactive measures like coordinated charging and V2G based load management could allow utilities to delay expensive infrastructure upgrades and improve the reliability of the supply as well as potentially reduce consumer costs. Nonetheless, there is still a lack of localised research that analyses these strategies based on real world feeder data and context specific participation patterns. Much of the current literature still relies on generic test networks or assumes universal V2G participation which might not be representative of the operational realities in the Nepalese distribution system.

1.1.5 Study Motivation and Approach

This research is motivated by the importance of implementing the theoretical advancements of the field of Vehicle to Grid (V2G) research into practical solutions for the unique environment of Nepal's distribution network. To overcome this, an extensive simulation model is created, which captures the realistic behavior of EV users such as arrival and departure patterns, partial participation in V2G, state of charge (SOC) reserve requirements and an economic evaluation based on time of use (TOU) tariffs. The proposed modelling framework is first applied to the real 11 kV Baneshwor radial distribution feeder and actual operational load data are used here to ensure that the analysis is not an abstraction and real network characteristics and user practices are reflected in the analysis. To prove the robustness of the method and its wider applicability, the same approach is then applied to the so-called radial distribution system named the IEEE-33 bus, which is generally recognized as a benchmark network for distribution studies. By performing this two step evaluation, the study presents specific technical and economic evidence of how coordinated V2G operation can reduce peak demand and improve daily load profile flattening, and deliver cost savings to EV owners. These findings are meant to provide information to plan future smart grid and formulate future policies, particularly in the case of developing power systems like Nepal, where reliable and economically viable integration of EV is important to build a stable and efficient, and sustainable electricity sector.

1.2 Problem Statement

The fast growth in the adoption of electric vehicles (EV) is putting increased pressure on electricity distribution systems in cities. This challenge is especially acute in the Kathmandu Valley where electricity demand is already high, daily load variations are large and the distribution network has limited flexibility to accommodate new, dynamic loads. Most existing low and medium voltage feeders are what were designed for traditional residential and commercial consumption, not for the large, mobile, and time dependent demand profiles associated with EV charging. The Baneshwor 11 kV radial feeder is a good example of the operational limitations of urban feeders under these changing conditions.

A key problem stems from the common behavior of EV charging. In uncontrolled scenarios, vehicles typically start charging as soon as they are plugged in, and then do not stop until a desired state-of-charge (SOC) is achieved. In practice, this often leads to a concentration of charging during evening hours as the users return home on the hours when residential demand is already at its peak. This clustering of behavior has the significant multiplier effect on feeder demand that occurs over short periods of time. As a result of increasing EV penetration the necessary load synchronization intensifies peak loading, increases transformer utilization, aggravates voltage deviations at the downstream buses and causes higher technical losses. Over time, this increased thermal stress increases the rate of aging of the equipment, ultimately leading to a decrease in feeder efficiency and compromising the reliability of the network. These technical challenges are compounded in the context of Nepal's distribution by other operational and structural challenges. Unlike highly automated systems, urban feeders in Nepal generally do not have elaborate real time monitoring systems, advanced distribution automation features, and robust demand side management mechanisms. This restricts the ability of utility to dynamically react to peak emergence or coordinating a flexible charging of EVs. Furthermore, tariff structures and incentive frameworks are still in a transition period when current pricing signals are not yet high enough to naturally shift charging away from peak demand periods. Consequently, uncontrolled charging is not only a technical issue for feeders, but also an economic issue for EV owners. Charging mostly during shoulder or peak tariff hours results in higher daily energy expenditure, which decreases the economic attractiveness of switching from conventional fuel-powered conventional vehicles to electric mobility.

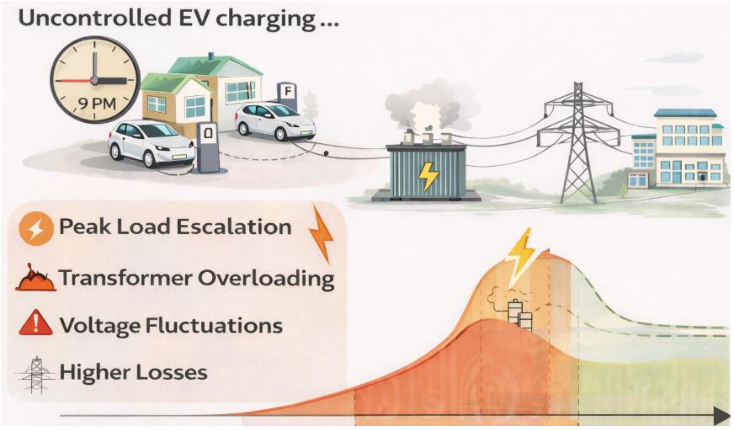

Figure 2:Evening Peak Load Escalation Due to Uncontrolled EV Charging

Vehicle to Grid (V2G) technology is well known as a promising solution for overcoming challenges of large-scale electric vehicle (EV) integration in terms of their operation and economical values. By supporting two-way power exchange, V2G enables EV batteries to act as distributed power storage systems that discharge power to the grid during demand peak periods and charge during low demand (valley) periods. In principle, this supports peak shaving, valley filling and overall load levelling, thus supporting improved feeder utilisation and reliability in the system. V2G also opens up the financial benefits for EV owners in the form of time of use (TOU) pricing structures and discharge credits. However, the actual performance of

V2G is affected by a variety of practical constraints that are either over-simplified or ignored in much of the existing literature.

A major limitation of existing studies is the use of idealized models, with typically complete participation of EV owners in V2G programs and neglect of realistic mobility behavior. In the case of actual deployment scenarios, V2G participation is partial, because not all EV owners are willing or able to allow battery discharge. EV availability is naturally uncertain and user specific plug-in and plug-out schedules dictated by daily travel routines. Battery protection is another critical issue, imposing stringent enforcement of state of charge (SOC) limits, reserve SOC for mobility, and target SOC at departure factors that limit the amount and time of energy discharge. In addition, the distribution feeder itself has special operation characteristics (such as its own load characteristics, peak load characteristics, and the radial network structure) that have a special influence on the technical effect of V2G at the local level. These real world complexities mean that the results based on simplified or generic assumptions may not be directly transferrable to feeders like Baneshwor in Kathmandu without rigorous contextual validation.

Therefore, this study addresses the critical gap of not having a realistic, feeder-level analytical framework to assess the coordinated V2G operation under the urban distribution condition in Nepal. There is an evident need for a simulation-based methodology that can quantify the effects of coordinated charging and discharging of EVs on feeder load profiles, peak demand and operational performance and explicitly incorporates realistic assumptions about user participation, mobility requirements and system constraints. Simultaneously, the framework needs to assess economic consequences for EV owners with TOU tariff structures, both charging costs, discharge credits and effects of battery degradation. Bridging this gap is vital to guide proper smart grid planning and to aid the reliable, cost effective integration of EVs into Nepal's distribution network as electric mobility adoption gains speed.

1.3 Objectives of the Study

The main objective of this research is to assess, in a practical and quantitative way, how the integration of the Vehicle-to-Grid (V2G) can improve the operational performance of the distribution feeders and the economic results for the electric vehicle (EV) owners in radial distribution networks. Rather than focusing only on the theoretical feasibility of the assessment, the focus here is on assessment under realistic operational conditions, such as EV availability patterns, partial participation in V2G, state of charge (SOC) protection limitations, and realistic time of use (TOU) pricing reflecting real consumer electricity billing.

In order to achieve this aim, the following specific objectives have been developed with the purpose of the study:

1. **Evaluate feeder load levelling performance under V2G compared to uncontrolled charging**
   Quantify the effect of coordinated V2G operation on changing the feeder load profile, compared to uncontrolled charging behavior. In uncontrolled situations EVs almost always start charging as soon as they are plugged in, which leads to demand clustering in high load periods. The opposite, V2G can coordinate charging and discharging to assist peak shaving and valley filling while ensuring mobility needs are met. This objective measures the extent of peak demand reduction, smoothing of daily load fluctuation and improvement of feeder level operational indicators with varying levels of EV penetration.
2. **Evaluate the economics of EV ownership using TOU tariff and V2G participation**
   Determine whether participation in V2G provides any tangible financial advantages to the EV owner, by calculating the net cost of charging per day in a realistic TOU tariff context. The analysis includes both the cost of importing charging energy and the credits received from the export of energy back onto the grid, and takes into account the degradation of the battery using a simplified throughput-based cost model. The goal is to quantify the average daily cost per EV as well as the percentage of cost savings realized under V2G operation, in order to establish whether the technical aspects of the grid can be recognized without compromising and potentially even improving owner's level economic outcomes.
3. **Demonstrate the practical applicability and generality of the proposed modelling framework**
   Verify the development of V2G framework to be practical and transferable by first

implementing and testing the developed model with real operational data from 11 kV Baneshwor radial distribution feeder of Kathmandu, Nepal (including 25 bus feeder model). This method ensures that the analysis is based on realistic feeder characteristics and demand patterns in the locality. To verify the broader applicability of a given framework, the same model is then applied to the widely known benchmark distribution study system known as the IEEE-33 bus radial distribution system. By comparing the performance enhancements in both systems, this goal provides evidence of the robustness, reliability and general relevance of the proposed V2G control approach.

1.4 Scope and Limitations of the Study

This study is designed around a practical question: how much can coordinated EV charging and V2G operation improve a radial distribution feeder's daily load profile, and can it also create measurable cost benefits for EV owners under a realistic tariff structure? To answer this, the work develops and evaluates a simulation based EV–V2G load levelling framework using both a real feeder case study and a standard benchmark feeder. The scope is intentionally focused on feeder level load shaping and owner side economics, while keeping the assumptions realistic and aligned with available data.

1.4.1 Scope of the Study

1. **Development of an EV–V2G load levelling framework**

   The core scope of this research is the development of a coordinated EV charging and discharging model that can represent three key realities:

   - EVs are not connected all day (availability windows matter),
   - Not all users allow V2G discharge (partial participation), and
   - EV batteries must still meet mobility needs (SOC reserve and departure SOC targets).

The framework is designed to operate over a one day scheduling horizon, divided into discrete time steps, and it generates a feasible charging/discharging schedule for EVs based on their constraints and feeder level objective.

2. **Application to a real feeder and a benchmark feeder**

   To ensure both practical relevance and academic comparability, the model is implemented on two systems:

   - Baneshwor feeder (25-bus radial model, 11 kV): used as the real world case study to reflect realistic loading behavior in Kathmandu Valley. The Baneshwor system is used to test the approach under practical demand patterns and feeder characteristics.
   - IEEE-33 bus radial distribution system: used to verify that the approach is not restricted to one local feeder and can be transferred to a widely used benchmark network for distribution studies.

This two step validation strengthens the credibility of the conclusions by demonstrating both local relevance and model generality.

3. **Penetration level based analysis**

   The study investigates the impact of EV adoption by simulating multiple penetration levels. The penetration range considered in the modelling spans 5% to 50%, allowing the study to observe how feeder performance and owner economics change as EV presence increases. This penetration based approach supports planning type conclusions, such as identifying ranges where uncontrolled charging creates significant stress and where coordinated V2G begins to provide more visible technical and economic value.

4. **Use of realistic system parameters and operational data**

   The Baneshwor feeder simulations are parameterized using available real world data and practical assumptions, including:

   - A representative NEA hourly load profile used to shape the daily base load pattern,
   - Distribution of bus loads to represent feeder demand allocation,
   - Feeder electrical characteristics such as line parameters (R/X),
   - EV charging and discharging power limits aligned with typical home/workplace chargers,
   - EV battery capacity ranges and SOC constraints consistent with practical EV usage, and

- Partial V2G participation rates to reflect realistic user willingness.

The intention is to keep the modelling grounded in operational reality rather than relying only on idealized assumptions.

5. **Feeder level load levelling performance assessment using KPIs**

   The primary technical evaluation is based on load profile improvement, using standard load levelling indicators. The following KPIs are included to quantify improvement:

   - Peak demand reduction (peak shaving): compares maximum feeder demand across scenarios.
   - Load Factor (LF): reflects how evenly the feeder is utilized over the day.
   - Flattening Index (FI): evaluates reduction in load variability (standard deviation comparison).

These KPIs are chosen because they directly describe feeder stress, utilization efficiency, and daily load smoothness, which are central to distribution planning.

6. **Economic analysis for EV owners under TOU pricing**

   In addition to feeder performance, the study evaluates whether EV owners obtain cost benefits. The economic assessment is based on a time of use (TOU) tariff, comparing net daily charging costs between uncontrolled charging and coordinated V2G operation. The cost formulation includes:

   - Charging cost based on TOU price at the time of charging,
   - Discharge credits based on export price assumptions, and
   - A battery degradation cost using a simplified throughput based coefficient.

This economic focus is important because V2G participation is unlikely to scale if it benefits only the grid while imposing hidden costs on EV owners.

7. **Model transferability and robustness**

   Finally, the study explicitly includes the transfer of the same framework from the Baneshwor feeder to IEEE-33 bus system without changing the conceptual logic. This part of the scope is aimed at showing that the modelling approach is robust and can be adapted beyond a single case study, which strengthens its suitability for broader planning discussions.

1.4.2 Limitations of the Study

While the study provides a detailed feeder level view of V2G based load levelling and EV owner economics, it is also bounded by modelling simplifications and scope decisions. These limitations are important to state clearly so that the results are interpreted correctly and future work can build on them.

1. **Simplified battery degradation modelling**

   Battery degradation is modeled using a linear cost per unit energy throughput. This approach is practical for feeder level studies, but it cannot fully capture the real electrochemical aging behavior of lithium-ion batteries. In reality, degradation depends on multiple factors such as:

   - Depth of discharge and cycle patterns,
   - Charge/discharge C-rate,
   - Operating temperature,
   - Average SOC level and SOC window, and
   - Calendar aging effects over time.

Therefore, while the degradation coefficient provides a useful approximation for economic comparison, the exact lifetime impact of repeated V2G cycling may differ from the simplified representation used here.

2. **Limited revenue streams (TOU-only economic framework)**

   The economic analysis considers only TOU based arbitrage and discharge credit compensation. In practical V2G programs, additional revenue streams may exist, such as:

   - frequency regulation,
   - reserve services,
   - voltage support,

- demand response incentives, or
- aggregator based market participation.

Because these additional services are not modeled, the study does not capture the full potential income that V2G could generate. As a result, the economic outcomes presented here should be interpreted as conservative and limited to TOU based operation.

3. **Participation modeling and behavioral uncertainty**

   The model assumes a fixed V2G participation ratio and assigns availability windows using realistic distributions. However, in real life, participation is dynamic and influenced by:

   - Daily travel variability,
   - User comfort and trust in V2G programs,
   - Battery warranty concerns,
   - Incentive levels, and
   - Charger accessibility and reliability.

Treating participation as constant simplifies the problem and supports consistent scenario comparison, but it may not fully reflect real world day to day behavior.

4. **Communication, control infrastructure, and implementation aspects not modeled**

   The study evaluates scheduling and impacts under the assumption that coordinated control is feasible. Practical deployment would also require communication infrastructure, charging station compatibility, metering, cyber security, and aggregator coordination mechanisms. These implementation level aspects are outside the scope of the simulation study but remain essential for real world adoption.

5. **Single day scheduling horizon and representative daily load shape**

   The scheduling horizon is one day, and performance is evaluated based on representative daily load profiles. Seasonal effects, long term EV growth, and day to day demand uncertainty are not explicitly modeled. Consequently, the results represent feeder performance for a typical operational day rather than a full year analysi

CHAPTER 2: LITERATURE REVIEW

2.1 Summary on Reviewed Papers

Coordinating large numbers of electric vehicles (EVs) so that they support distribution feeders rather than stressing them is now a practical requirement. Recent research indicates that if EV flexibility is arranged in terms of aggregators, then it can be applied to the re-shape of feeder net-load profiles and reduce operational stress. In particular, coordinated action among multiple aggregators enhances peak shaving and valley filling along with the solution of EV energy needs and feeder-level constraints [1]. Once feeder constraints have been incorporated in the control objective, voltage regulation will be just as important as peak reduction. Coordinated charging and discharging strategies have been demonstrated to effectively manage supply voltages while taking into consideration the benefit on the customer side, which is a strong argument for feeder-aware V2G scheduling over price-based charging only [2].

More recently, hierarchical coordination has also been implemented in order to overcome the congestion and capacity limitations of hosting infrastructure, and it has been shown that structured, multi-layer control can allow an increase of penetration of electric vehicles while keeping the distribution networks within operating limits [3]. One of the biggest obstacles to sustained V2G participation is the battery. The literature places a strong emphasis on the fact that frequent cycling and deeper charge swings can be detrimental to battery degradation, and so technical feasibility must be coupled with ageing-aware operation if V2G is to be realistic at scale [4]. In parallel, TOU/ToD pricing still is a major tool on which charging behaviour can be shaped. Methods for estimation and implementation of TOU tariffs for EV-centered demand-side management endorse the usage of time-varying prices to decrease peaks and shift demand into off-peak windows in a quantifiable manner [5]. Because there is a monetary aspect of degradation, the more recent work is to connect V2G cycling to compensation models, arguing any economic assessment of V2G should account for the cost of degradation so that it is fair and sustainable [6]. At the same time, broader EV technology reviews recap the change in electricity demand patterns caused by EV adoption and resulting in both risks (new peaks) and opportunities (flexible load and storage) that helps to situate the feasibility studies at feeder level in the broader context of transition towards electrified transport [7]. Beyond control and economics, communication and information infrastructure is a practical dependency for coordinated charging. Smart grid communication surveys point to the need for reliable efficient information exchange in order to provide large-scale coordination, and to support responsive control under operational constraints [8]. Lifecycle considerations are also examined in the literature through second-use battery strategies which demonstrate that retired EV batteries can still deliver utility services and affect overall EV economics serving as a relevant comparison point for using in-vehicle batteries for grid support [9]. V2G impact analyses further link these themes by addressing the interaction of EVs with smart grids and the dependence of grid services on the chosen control strategy and approach to grid integration and how this can strengthen the need for structuring coordination instead of ad hoc charging behavior [10]. Foundational V2G work establishes how EVs can provide power capacity and potential revenue streams, which is still useful to frame what kinds of services EV fleets can theoretically provide, and what value categories are usually considered [11]. Early distribution studies also show that unmanaged charging can result in local stress to residential grids, providing support to the basic motivation for coordinated scheduling and feeder-level constraint management [12]. System-level integration studies widen the context by describing the role of EVs within the overall operation and planning of the power system, which assists in justifying the role of aggregators as interface between the individual vehicles and grid-level goals [13]. Practical charging infrastructure constraints are also important, as charger topology and charging power levels have direct implications on the outcome of what scheduling can achieve and what assumptions are likely to be realistic for feeder-level simulations [14].

Real-time coordination approaches show that EV charging can be actively managed to reduce losses and improve voltage profiles, providing strong support for studies that include voltage compliance and operational quality (not only energy cost) as part of the objective [15]. As renewable penetration increases, charging strategies that incorporate renewable availability or staged decision-making illustrate how EV scheduling can be aligned with variable generation while still meeting mobility needs and grid limits [16]. At last, decentralized control methods address scalability and privacy concerns by coordinating large EV populations without requiring full centralization, which aligns well with aggregator-based implementations designed for real feeders and realistic fleet sizes [17]

CHAPTER 3: METHODOLOGY

3.1 Flowchart of proposed model

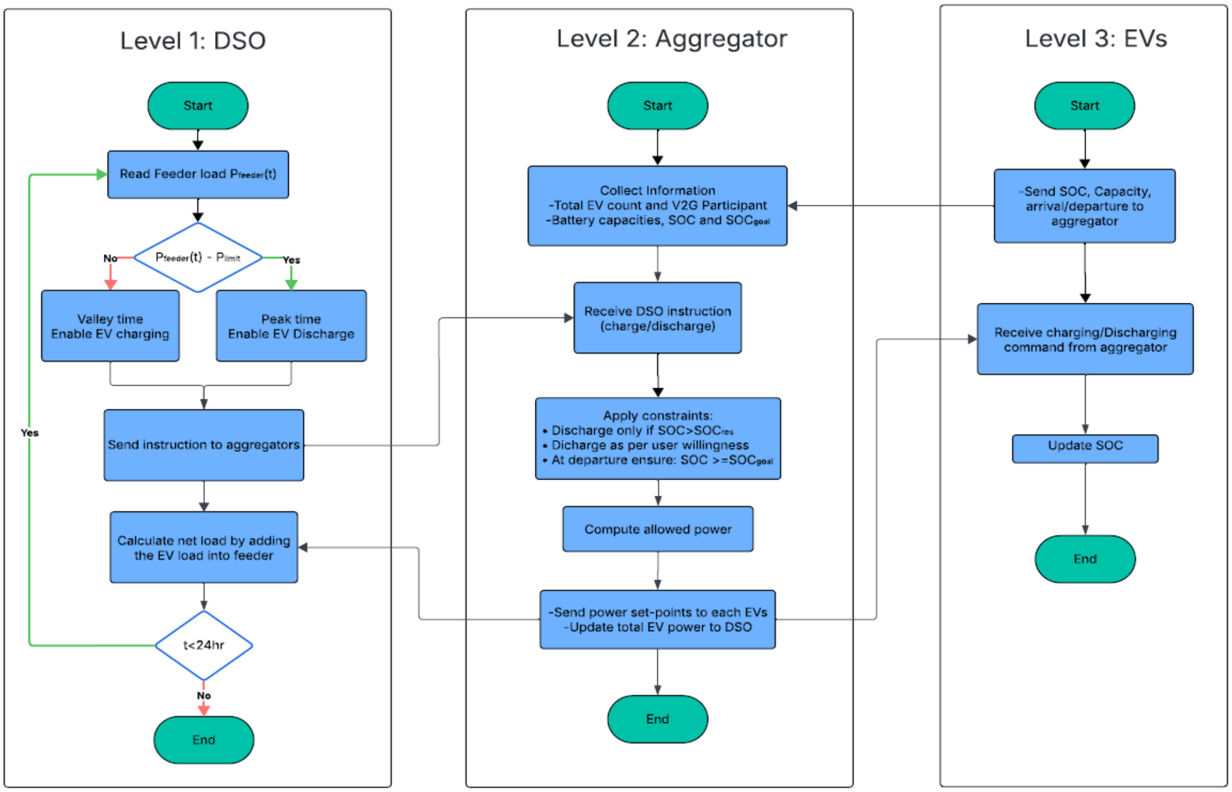

Figure 3 : Control flowchart of the proposed model at three levels

The proposed Vehicle-to-Grid (V2G) flowchart is organized in three levels of hierarchy and it involves the interaction between the Distribution System Operator (DSO), Aggregators, and Electric Vehicles (EVs). The flow chart is used to show the step by step procedure of dealing with EV charging and discharging using V2G technology to optimize the performance of the grid and reach load levelling. The explanation of every level and functioning is clear as given below.

Level 1: Distribution System Operator (DSO)

The top down level is in-charge of managing the overall grid load, and integrating with aggregators to control EV charging and discharging. The process begins with the measurement of the current feeder load, $P_{feeder}(t)$, which is used to reflect the real time demand of the distribution network in regard to electricity. This value is contrasted with a predetermined value, P_{limit}, which is used as an objective of load balancing. By this comparison the DSO ascertains the system to be in peak conditions or in valley conditions:

- Valley Time: When $P_{feeder}(t)$ is below P_{limit} (off-peak period), the DSO instructs aggregators to enable EV charging, allowing vehicles to draw energy from the grid.
- Peak Time: When $P_{feeder}(t)$ exceeds P_{limit} (peak period), the DSO instructs aggregators to initiate EV discharging, so EVs can supply stored energy back to the grid.

Once the correct mode (charging or discharging) has been found, the DSO sends the instructions to the aggregators who update the energy status of the system. This control mechanism is a daily round-the-clock process with a 24 hour time frame, and balances the real-time load effectively. After 24 hours have passed, then the process ends.

Level 2: Aggregators

Aggregators are required to act as intermediaries between the DSO and the individual EVs in coordinating the involvement of EV fleets in V2G activities as directed by the DSO.

- Information Collection: Aggregators obtain vital data such as the number of connected EVs, V2G participation rate and battery parameters of a specific EV such as current State of Charge (SOC) and SOC_{goal} (target charge level).
- Receiving DSO Instructions: Aggregators receive charging or discharging orders on the DSO, and impose critical constraints on coordinate battery control.
- SOC Constraints: Aggregators make sure that each EV's SOC remains above a defined reserve threshold (SOC_{res}) to guarantee mobility, and within SOC_{goal} and SOC_{min} to protect battery health.

- Power Allocation: The aggregator determines the power that each EV is allowed to charge or discharge based on the SOC constraints and the fleet status. Such power set points are then sent as commands to individual EVs.
- Reporting: The cumulative power (addition of all the controlled EVs) is reported back to the DSO, allowing real time grid load adjustment.

Level 3: Electric Vehicles (EVs)

Individual EVs on this level interface directly with the aggregator and respond using whatever they are told to either charge or discharge based on what is demanded by the grid.

- Data Reporting: Every EV also reports its SOC, its battery capacity, and arrival/departure to the aggregator, which enables it to schedule its operations in real time, optimally.
- Executing Commands: EVs are supplied with and assessed charging or discharging points by the aggregator. Charging audit raise SOC, whereas discharge reduces SOC.
- SOC Update: The SOC of any EV is updated in real time during charging/discharging in order to represent the actual battery condition.
- Plug Out Handling: When unplugging, the SOC of the EV is set to be at or above SOC_{goal}, which guarantees the mobility of the owner and his/her further journeys.

This control hierarchy therefore allows the DSO to manage grid wide functionality, aggregators to coordinate group level V2G participation and individual EVs to react flexibly to grid requirements and user demands. The strategy will be aimed at better grid stability, less peak load stress, and consistent economic gain of EV owners via controlled V2G participation.

3.2 System description and load modelling

The paper examines the effect of Vehicle to Grid (V2G) integration on two model radial distribution systems the IEEE 33-bus test system and Baneshwor radial system of Kathmandu, Nepal. IEEE 33 bus system is used as a benchmark to compare and verify the developed MATLAB simulation framework and to guarantee that the model is relatively stable, when operating in the conditions that are widely accepted. By contrast, the Baneshwor feeder is a real world case study, which means that the model can be tested in real operating conditions and real load patterns peculiar to Kathmandu context. The study takes the form of a benchmark and real feeder by ensuring that the developed V2G framework is academically rigorous and practically relevant.

3.2.1 IEEE 33 Bus Radial distribution system

IEEE 33 bus test system is a famous benchmark network that is largely used in distribution load flow and optimization research work. It is made up of 33 buses and 32 branches and the nominal voltage is 12.66 kV and total active and reactive load is about 3.72 MW and 2.30 MVAr respectively. This is a single substation fed system, and is a typical urban radial feeder consisting of mixed residential and commercial loads.

Table 1: Summary of IEEE 33-Bus System Parameters

Parameter	Value	Description
Number of buses	33	Total distribution nodes
Number of lines	32	Radial branches
Base voltage	12.66 kV	System nominal voltage
Base power	10 MVA	Reference power for p.u. conversion
Total active load	3.72 MW	Aggregate demand
Total reactive load	2.30 MVAr	Aggregate reactive demand
Topology	Radial	Single-source distribution network

The system parameters, such as line resistance, reactance, and bus loads, are implemented in per unit (p.u.) form using a 12.66 kV base voltage and 10 MVA base power. This test system was selected because its radial topology closely resembles typical Nepali distribution feeders in configuration and loading behaviour.

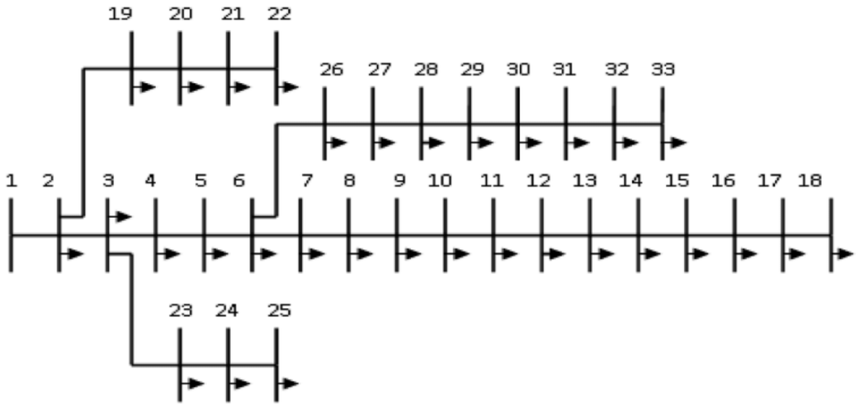

Figure 4: SLD of a IEEE 33 Radial System

3.2.2 Baneshwor feeder configuration

This paper explores how Electric Vehicle (EV) aggregators can be integrated and coordinated in the 11 kV radial distribution feeder called Baneshwor. The feeder includes several nodes of distribution and radial branches that include 24 load points (L2-L25) which are fed by one substation. The model can simulate such strategies of load management as peak shaving and valley filling through managing the charging and discharging cycles of EVs operating on the network.

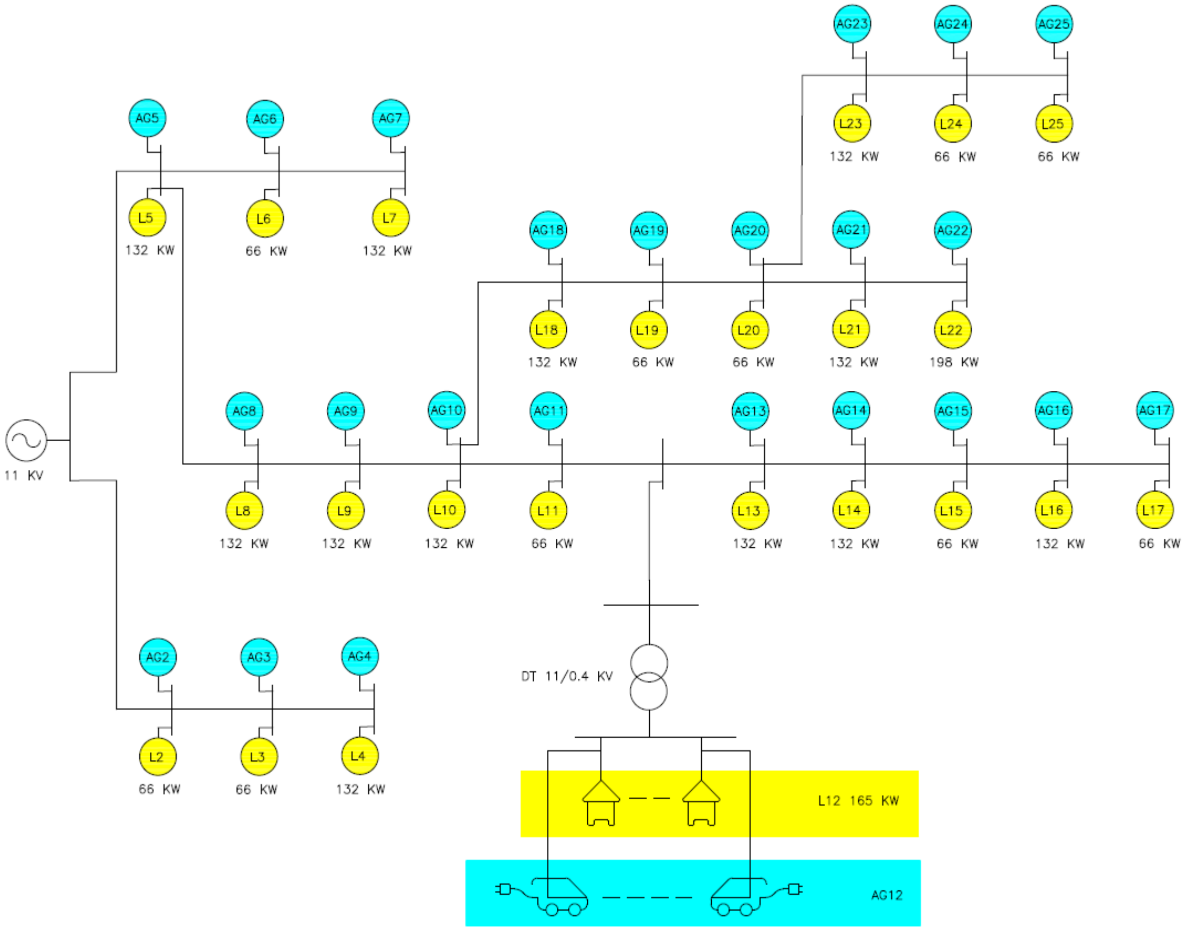

Figure 5: Baneshwor feeder configuration

- **Load Points and Aggregators**: The distribution system has 25 buses and 24 radial branches, which serve a wide range of commercial, residential, and EV charging loads. The EVs are controlled at each load point by aggregators (AG2-AG25), which control the distribution of power as well as to make sure that EV charging and discharging is done according to the availability of EVs and grid needs.
- **Power Distribution**: The system has a base needs of 11 kV with an active peak load need of 2.6 MW. Distribution is assigned dynamically based on the real-time requirements by a two level coordination system comprising of Distribution System Operator (DSO) and aggregators.

- **Energy Management**: Every aggregator manages its respective EVs to facilitate charging during off-peak hours and discharging during peak hours, which would decrease the volatility of the loads. This is regulated by a hierarchical format: the DSO establishes power allocation objectives and each aggregator achieves the objectives by the charging/discharging timetables of its affiliated EVs.

Table 2: Summary of Baneshwor feeder System Parameter

Parameter	Value	Description
Number of buses	25	Total distribution nodes
Number of lines	24	Radial branches
Base voltage	11 kV	System nominal voltage
Active peak load	2.6 MW	Aggregate feeder demand
Topology	Radial	Single-source distribution network
Load composition	Mixed	Commercial+Residential + EV charging

3.3 Daily profile generation

For the simulation of the distribution network, the time varying base load at each bus (denoted as $P_i(t)$ for active power and $Q_i(t)$ for reactive power) is generated using normalized daily load profiles derived from the NEA feeder data and representative demand profiles. The load at each node is expressed as:

$$P_i(t) = P_{i,nom}\, f(t) \tag{1}$$

$$Q_i(t) = Q_{i,nom}\, f(t) \tag{2}$$

Where,

$P_{i,nom}$ and $Q_{i,nom}$ represent the nominal active and reactive power at bus ‘i’

f(t) is the normalized hourly load shape function with mean value = 1.

The f (t) is a combination of several Gaussian components representing the morning and evening spikes of electricity demand, therefore, providing a realistic daily pattern of fluctuation as shown in Figure 6. This method can represent the actual variability of demand in the real world in a more accurate way and is needed to continue the simulations of Electric Vehicle (EV) and Vehicle to Grid (V2G) loads.

The process of this time series modeling is the basis of the simulation of bus level demand and then applied to analyze energy flow, such as EV and V2G system integration. This approach will enable more accurate grid stability and optimal energy management predictions with the rising EV adoption.

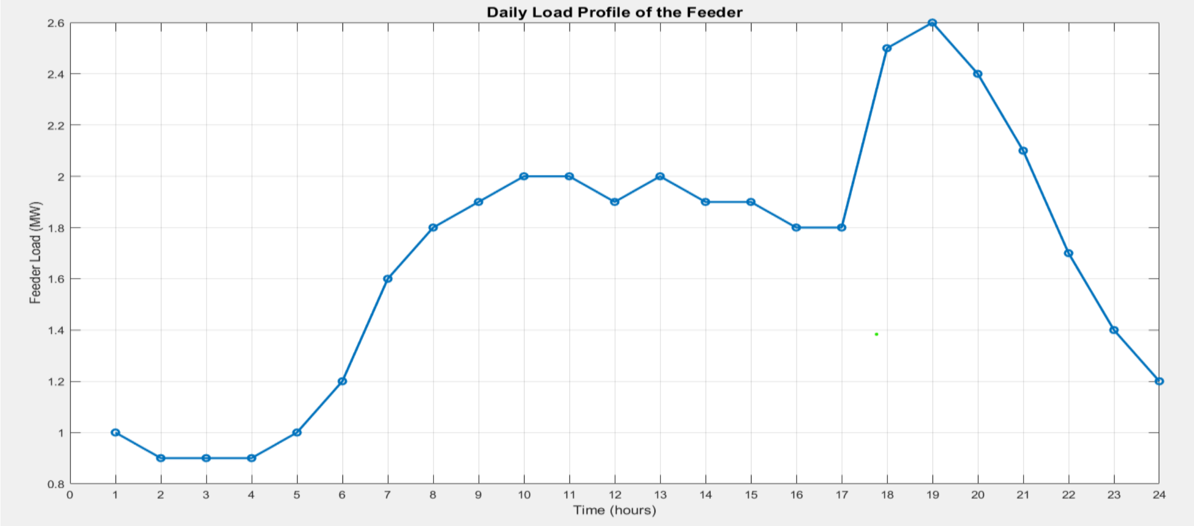

Figure 6: Daily Load Profile for Base (Non-EV) Demand

3.4 EV Electrical and operational parameters

In this study, the battery charging and Electric Vehicle (EV) parameters are assumed as follows for the simulation of energy management and grid integration:

Table 3: EV Battery and Charging Parameters used in the simulation

Parameter	Symbol / Unit	Assumed Value / Range	Description / Source
Nominal battery capacity	E_{cap} (kWh)	40 – 60 (mean ≈ 52)	Typical mid-range EV battery [1]
Initial SOC	SOC_0	10 – 40 %	At grid connection start
Target SOC	SOC_{goal}	75 – 100 %	Desired by owner before next trip
Minimum SOC	SOC_{min}	10 %	Battery protection threshold
Reserve SOC for V2G	SOC_{res}	30 %	Minimum retained energy for mobility

Max charging power	P_{ch}^{max}(kW)	7.2	Single phase level-2 charger
Max discharging power	P_{dis}^{max} (kW)	6.0	V2G inverter limit
Charging efficiency	η_{ch}	0.94	Converter and cable losses
Discharging efficiency	η_{dis}	0.94	Converter efficiency
V2G participation ratio	r_{v2g}	40 % of connected EVs	Fraction willing to discharge
Simulation time step	Δt	5 min	Temporal resolution
Time horizon	–	24 h	Daily operation window

- **Nominal Battery Capacity:** Typical EV batteries are assumed to have capacities ranging from 40 kWh to 60 kWh, with an average value of 52 kWh, reflecting common mid range EV models.

- **State of Charge (SOC):** The initial SOC at the time of grid connection is assumed between 10% and 40%. The target SOC required before the next trip is set between 75% and 100% to ensure optimal performance, while a minimum SOC threshold of 10% is enforced for battery protection.

- **Reserve SOC for V2G:** To guarantee sufficient energy for mobility, a reserve SOC of 30% is maintained for V2G operations.

- **Charging and Discharging Power:** Maximum charging power is limited to 7.2 kW (single phase Level-2 charger). For V2G applications, the maximum discharging power is capped at 6.0 kW, in line with typical inverter capabilities.

- **Efficiency:** Both charging and discharging efficiencies are set at 0.94, accounting for converter and cable losses during both operations.

- **V2G Participation Ratio:** It is assumed that 40% of connected EVs participate in discharging, depending on their availability and the coordination mechanism.

- **Simulation Time-Step:** The simulation uses a temporal resolution of 5 minutes, which provides sufficient granularity to capture time varying loads and V2G interactions.

- **Time Horizon:** Each simulation run covers a 24-hour period, representing a full daily operation cycle.

3.5 TOU Tariff

To reflect practical price variation over the day, a three tier TOU tariff based on the Nepal Electricity Authority (NEA) structure was adopted. Energy rates differ across peak, shoulder, and off-peak periods to encourage load shifting.

Table 4: Time-of-Use Tariff Applied in Simulation

Period	**Time Interval (hours)**	**Tariff (NPR/kWh)**	**System Context**
Off-Peak	23:00 – 05:00	3.7	Low demand period – encouraged for EV charging
Shoulder	05:00 – 17:00	8.4	Moderate load – daytime operation
Peak	17:00 – 23:00	9.35	High demand – preferred for V2G discharge

3.6 Problem Formulation

A radial distribution feeder is operated by a Distribution System Operator (DSO). The scheduling horizon is one day, divided into T time steps of duration Δt (hours). Let the base (non EV) feeder load be $P_{base}(t)$ (kW). EVs are connected to the feeder through a set of aggregators A, where aggregator a∈A supervises a group of EVs, i∈Ia connected at a particular transformer/load point .

- **Feeder load model (DSO view):**

At each time step t, total feeder load becomes:

$$P_{feeder}(t) = P_{base}(t) + \sum_{a\epsilon A} \sum_{i\epsilon I_a} \left(P_{a,i}^{ch}(t) - P_{a,i}^{dis}(t) \right) \tag{3}$$

Charging increases feeder load, discharging reduces feeder load.

The DSO defines a reference operating level P_{limit} as the average feeder load under the uncontrolled charging case:

$$P_{limit} = \frac{1}{T} \sum_{t=1}^{T} P_{feeder}^{un}(t) \tag{4}$$

- **Objective function (DSO load levelling)**

The DSO aims to flatten the feeder load around P_{limit} by coordinating the aggregator set point

$$Min \sum_{t=1}^{t} \left(P_{feeder}(t) - P_{limit}\right)^2 \tag{5}$$

This reduces peaks and valleys by penalizing any deviation from P_{limit}.

- **Subject to constraints:**

1. Charger and inverter limits

When connected, EV power is bounded by charger and V2G inverter ratings:

$$0 \leq P_{a,i}^{ch}(t) \leq P_{ch}^{max} \quad \text{(Charging)} \tag{6}$$

$$0 \leq P_{a,i}^{dis}(t) \leq P_{dis}^{max}) \quad \text{(Discharging)} \tag{7}$$

2. Availability constraint (plug-in windows)

Let $u_{a,i}(t) \in \{0,1\}$ indicate whether EV 'i' is connected at time t. If the EV is not plugged in, it cannot exchange power:

$$0 \leq P_{a,i}^{ch}(t) \leq u_{a,i}(t) P_{ch}^{max} \tag{8}$$

$$0 \leq P_{a,i}^{dis}(t) \leq u_{a,i}(t) P_{dis}^{max} \tag{9}$$

If $u_{a,i}(t) = 0$, both charging and discharging are forced to zero.

3. Partial V2G participation (who is allowed to discharge)

Let $v_{a,i} \in \{0,1\}$ represent whether EV 'i' participates in V2G:

$v_{a,i} = 1$ can discharge
$v_{a,i} = 0$ cannot discharge

$$0 \leq P_{a,i}^{dis}(t) \leq v_{a,i}\, u_{a,i}(t) P_{dis}^{max} \tag{10}$$

Non-participating EVs ($v_{a,i} = 0$) will always have $P_{dis} = 0$.

4. No simultaneous charge and discharge

To avoid charging and discharging at the same time, a binary mode variable $z_{a,i}(t) \in \{0,1\}$ is introduced:

$z_{a,i}(t) = 1$: charging mode

$z_{a,i}(t) = 0$: discharging mode

$$0 \le P_{a,i}^{ch}(t) \le z_{a,i}(t)u_{a,i}(t)P_{ch}^{max} \tag{11}$$

$$0 \le P_{a,i}^{dis}(t) \le (1 - z_{a,i}(t))v_{a,i}\, u_{a,i}(t)P_{dis}^{max} \tag{12}$$

This makes sure only one of the two can be positive at a time step.

5. SOC limits and reserve SOC (battery protection + mobility)

Battery protection is enforced by SOC bounds:

$$SOC_{min} \ \le \ SOC_{a,i}(t) \le SOC_{max} \tag{13}$$

To ensure mobility, discharging is only allowed if the EV stays above a reserve level:

$$P_{a,i}^{dis}(t) > 0 \; whenever \; SOC_{a,i}(t) \ge SOC_{res} \tag{14}$$

6. Target SOC requirement at departure (owner requirement)

Let $t_{a,i}^{dep}$ be the departure time step for EV 'i'. The EV must meet the desired SOC by departure:

$$SOC_{a,i}(t_{a,i}^{dep}) \ge SOC_{goal} \tag{15}$$

This ensures V2G does not compromise the owner's next trip.

7. SOC dynamics with efficiencies

Let $E_{a,i}$ be battery capacity (kWh), η_{ch} and η_{dis} be efficiencies. SOC updates as:

$$SOC_{a,i}(t+1) = \ SOC_{a,i}(t) + \frac{\eta_{ch}P_{a,i}^{ch}(t)\Delta t}{E_{a,i}} - \frac{P_{a,i}^{dis}(t)\Delta t}{\eta_{dis}E_{a,i}} \tag{16}$$

Charging increases SOC (with efficiency). Discharging decreases SOC (considering loss).

8. EV owner cost formulation under TOU tariff

A time of use (TOU) electricity price p(t) (NPR/kWh) is applied over the 24-hour horizon. For each day, the net daily cost for an EV owner is computed as the charging cost minus the discharge revenue plus a battery degradation cost:

$$C_{total} = \ C_{ch} - C_{dis} + C_{deg} \tag{17}$$

where $P_{ch}(t) \geq 0$ is the EV charging power (kW), $P_{dis}(t) \geq 0$ is the EV discharging power (kW), and Δt is the time step (hours). The charging cost is:

$$C_{ch} = \sum_{t=1}^{T} P_{ch}(t)\, p(t)\Delta t \tag{18}$$

and the discharge credit (revenue) is:

$$C_{dis} = \sum_{t=1}^{T} \alpha P_{dis}(t)\, p(t)\Delta t \tag{19}$$

Battery degradation is approximated using a linear cost per unit battery throughput c_{deg} (NPR / kWh). Using charging and discharging efficiencies η_{ch} and η_{dis}, the degradation cost is modeled as:

$$C_{deg} = c_{deg}\left(\eta_{ch}\sum_{t=1}^{T} P_{ch}(t)\,\Delta t \;+\; \frac{1}{\eta_{dis}}\sum_{t=1}^{T} P_{ch}(t)\,\Delta t\right) \tag{20}$$

In this study, $c_{deg} \approx 0.50$ NPR/kWh of battery throughput.

Finally, the daily net benefit of V2G participation is evaluated by comparing the uncontrolled charging case with the coordinated V2G case:

$$\Delta C = C_{un} - C_{v2g} \tag{21}$$

- $\Delta C > 0$: owner saves money with V2G
- $\Delta C = 0$: neutral
- $\Delta C < 0$: V2G increases cost

3.7 EV Plug-in Availability and V2G Participation Pattern (10% Penetration)

The EV plug-in availability heat map under the situation of 10 % EV penetration is presented in figure 7. The individual electric vehicles are shown by the rows of the figure and the time horizon of 24 hours a day is the horizontal axis. The color scheme will indicate the connections status of the EVs and V2G participation of the vehicles on the time step: blue will indicate that the vehicle has not connected to the grid, red will indicate the vehicles (that are connected to the grid but operate in the charging-only (G2V) mode), and yellow will indicate the vehicles that are connected to the grid and have the opportunity to engage in the V2G discharging. It is obvious that the patterns of the EV availability are not moving throughout the day and have realistic mobility patterns, which can be clearly seen in the heat map. The grid-tied home many of the vehicles are operated by the grid in the late evening and night time hours much like the residential charging patterns where users get home after spending the entire day travelling. During such periods, the related EVs in yellow are prominent in large numbers which implies that they can take part in V2G when the control strategy requires them. On the other hand, throughout the day, and particularly in the morning and late afternoon, most EVs are blue and therefore they are not tied to the grid. This denotes commuting and utilization trends during the day where the vehicles are not interconnected and, therefore, they cannot form part of the grid. Only a subset of EV is still linked together at this point, primarily consisting of users that might have access to charging at the workplace or they have elastic mobility hours. An important observation of the heat map is that there is a greater difference between the EVs that are connected and cannot be discharged (red) and those that are fully V2G enabled (yellow). This visual difference underlines the assumption of half-v2g of the involved model. A large percentage of the vehicles are not permitted or inclined to put energy back at the grid even when plugged. This shows the actual state of the real world where the interest of the users, battery problems and bonus programs dictate the attendance rates. Overall, it can be stated that the heat map reveals that the availability of V2G is inherently constrained regarding the patterns of time connections, along with participation options. Evening and night time hours of V2G-capable EVs are also corresponding to the system requirements since evening and night time hours are associated with the upsurge of loading of the feeder and peak loads. This implies that a minimal degree of penetration of 10 percent would enable a coordinated V2G operation to provide the necessary flexibility to load levelling without necessarily having impractical, full-day EV availability. This worth therefore confirms that the modeling framework model is the true reflection of the actual EV behavior, and a realistic basis to conclude on technical and economic implications of V2G integration at the feeder level.

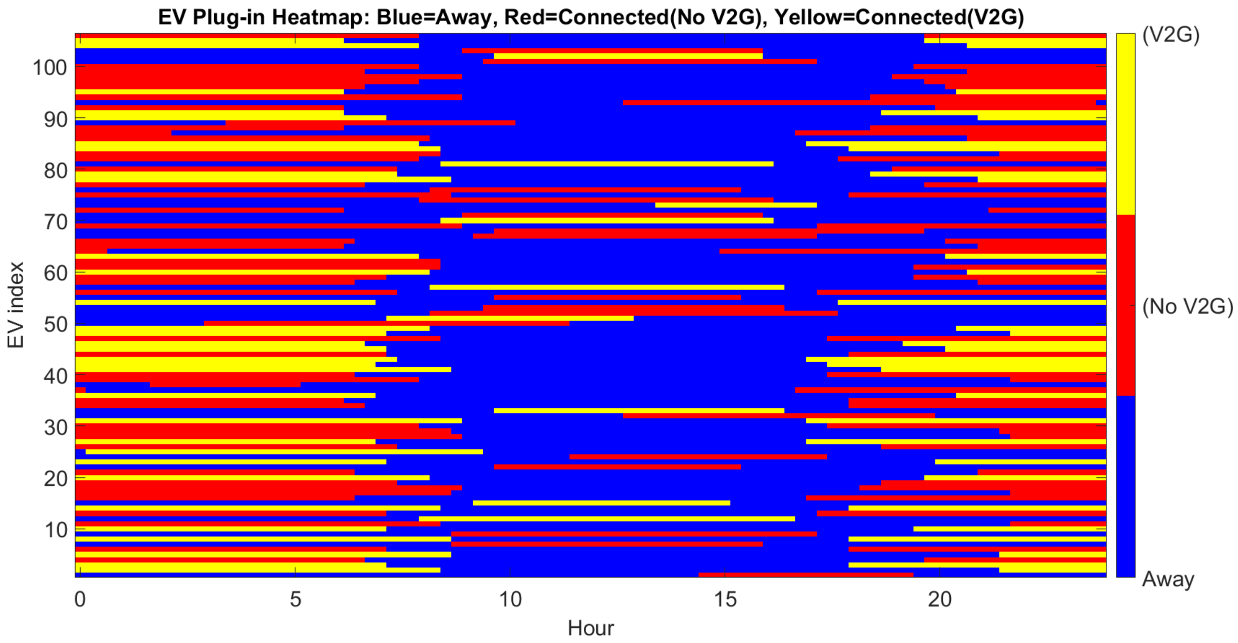

Figure 7: EV Plug-in Availability and V2G Participation Pattern (10% EV Penetration)

3.8 Key Performance Indicators

To systematically evaluate the effectiveness of the proposed Vehicle to Grid (V2G) framework, this study adopts a set of well defined Key Performance Indicators (KPIs). These KPIs are selected to comprehensively measure both the technical performance of the distribution feeder and the economic outcomes for electric vehicle (EV) owners. By comparing scenarios of uncontrolled EV charging with those of coordinated V2G operation, the KPIs enable an in-depth assessment of how V2G integration affects load levelling, grid operational efficiency, and user cost savings.

For clarity and focused analysis, the KPIs are organized into two main categories:

- Load profile flattening indicators, which evaluate feeder level performance improvements, and
- Cost benefit indicators, which assess the economic advantages for EV owners.

3.8.1 Load Profile Flattening Indicators

Load profile flattening indicators are used to evaluate how effectively V2G integration mitigates peak demand and enhances the overall utilization of the distribution feeder. As reducing stress on distribution infrastructure is a primary motivation for V2G deployment, these indicators directly reflect the technical benefits of coordinated EV operation.

1. Feeder Peak Load Comparison (Uncontrolled vs V2G)

The most direct indicator is the comparison of maximum feeder peak load under two scenarios: uncontrolled EV charging and coordinated V2G operation. In the uncontrolled case, EVs typically begin charging immediately after arrival, often during evening hours when residential demand is already high, resulting in a sharp increase in peak load.

In the V2G scenario, EV charging and discharging are actively coordinated. Charging is shifted toward low demand periods, while discharging is encouraged during peak hours. Consequently, the feeder peak load is reduced via peak shaving. A significant reduction in peak demand under the V2G scenario demonstrates that EVs are effectively supporting grid operation rather than exacerbating congestion.

2. Load Factor (LF)

The Load Factor is a widely used indicator that measures how efficiently electrical energy is utilized over a given period. It is defined as the ratio of the average load to the peak load:

$$LF = \frac{P_{avg}}{P_{peak}} \tag{22}$$

where P_{avg} represents the average feeder load over the day and P_{peak} represents the maximum load observed during the same period.

A higher load factor signifies that electrical demand is more consistently distributed throughout the day, which is advantageous for both operational reliability and cost Yes effectiveness. Systems with a low load factor endure intense peaks for brief periods, causing infrastructure to remain underused for much of the day and increasing the potential for equipment stress and inefficiencies. Implementing V2G operation helps flatten the load profile by shifting energy usage and supporting peak shaving, thereby lowering maximum demand without significantly affecting the average load. This results in a higher load factor, indicating better utilization of feeder assets and enhanced overall system efficiency. An observed increase in LF under V2G scenarios thus serves as a key indicator of improved feeder performance and more effective energy management.

3. Flattening Index (FI)

While peak load reduction and load factor improvement provide valuable insights into feeder performance, they do not fully capture how evenly the load is distributed throughout the day. To address this, the Flattening Index (FI) is employed to evaluate the overall smoothness of the feeder load profile.

The FI quantifies the relative reduction in load variability achieved through coordinated V2G operation compared to uncontrolled EV charging. Load variability is measured by the standard deviation of the feeder load over the scheduling horizon.

The Flattening Index is defined as:

$$FI = 1 - \frac{\sigma_{V2G}}{\sigma_{un}} \tag{23}$$

where:

σ_{V2G} is the standard deviation of the feeder load profile under V2G operation, and

σ_{un} is the standard deviation of the feeder load profile under uncontrolled EV charging.

The standard deviation σ is calculated as:

$$\sigma = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(P(t) - \bar{P})^2} \tag{24}$$

where:

$P(t)$ is the feeder load at time step t,

$\bar{P}$ is the average feeder load over the day, and

T is the total number of time steps.

Interpretation:

FI = 0: No improvement in load smoothness compared to uncontrolled charging.

FI > 0: Reduction in load fluctuations due to V2G integration.
Higher FI values: Greater flattening of the load profile and improved feeder stability.

As a normalized, relative measure based on standard deviation, the FI facilitates intuitive performance comparison across different scenarios and EV penetration levels, independent of absolute load magnitude.

3.8.2 Cost Benefit Indicators for EV Owners

Beyond technical performance, the economic feasibility of V2G participation is a decisive factor for EV owner engagement. To assess whether V2G delivers tangible financial benefits to users, this study employs specific KPIs under a time-of-use (TOU) tariff framework.

1. Daily Energy Cost per EV (Uncontrolled vs V2G)

This KPI evaluates the average daily energy expenditure of an EV owner under two scenarios: uncontrolled charging and coordinated V2G operation. In the uncontrolled scenario, EVs typically charge during periods of high electricity tariffs, resulting in elevated costs. Conversely, V2G coordination leverages off-peak charging at reduced rates and enables energy discharge to the grid during expensive peak-tariff windows, thereby generating additional revenue or credits for the owner.

The calculation of this KPI accounts for all relevant cost components, including the cost of energy for charging, revenue from discharging (discharge credits), and battery degradation expenses. By reflecting the net daily cost impact, this metric offers a realistic comparison of owner expenses between the two charging strategies. A lower daily cost in the V2G scenario clearly demonstrates the economic advantage of coordinated operation for EV users.

2. Percentage Daily Cost Saving per EV

To express the economic benefit in relative terms, the percentage daily cost saving per EV is calculated as:

$$\%\ \text{Saving} = \frac{C_{un} - C_{V2G}}{C_{un}} \times 100\% \tag{25}$$

where C_{un} represents the daily cost under uncontrolled charging and C_{V2G} represents the daily cost under coordinated V2G operation.

This metric quantifies the relative reduction in daily energy expenses for EV owners who participate in V2G programs. A higher percentage saving reflects a greater financial incentive for users, making V2G participation more appealing. By presenting cost savings as a proportion of the original expense, this KPI allows for an intuitive assessment of the economic attractiveness of V2G integration, regardless of absolute cost levels or varying electricity tariffs. It thus directly captures the user's financial motivation to engage in V2G operations.

3.9 Sensitivity Analysis of EV Owner Net Benefit

The financial feasibility of Vehicle-to-Grid (V2G) participation to EV owners is very delicate to a number of key factors, including electricity rates, compensation of discharged energy, and the cost of battery degradation. Due to the fact that these variables are both subject to regulatory changes and market uncertainty this research paper conducts a sensitivity analysis to determine how changes in the key economic inputs will impact the net benefit of V2G operation in the eyes of the owner.

The main purpose of such sensitivity analysis is to identify the threshold conditions under which V2G participation can be economically appealing, neutral, or not, and EV owners. It is achieved through the comparison of daily net energy costs per case of operating conditions in two scenarios:

- Uncontrolled charging:
  The EV is charged as soon as the plug is in the highest possible rate until the desired state of charge (SOC) is has been met. When the target SOC is attained, the car will not move until it is time to leave and no discharge to the grid will be allowed.
- V2G-controlled operation:
  The proposed control structure is used to optimize the charging and discharging schedule. Charging becomes a priority when the tariff is low and discharging when tariff is high (peak) and the charger limit is considered, reserve SOC limit and the target SOC must be achieved at the time of departure.

In order to make a fair and consistent comparison, the populations of all the EVs as well as, their respective availability windows and mobility needs are the same; the only difference is in the control strategy of charging and discharging.

The net economic value of the EV owner is determined by the difference between the daily cost at uncontrolled charging and the V2G operation:

$$\varDelta C = C_{\text{uncontrolled}} - C_{\text{V2G}} \tag{26}$$

A high figure means that V2G has been shown to reduce the daily cost of energy of the owner and is therefore cost-effective. A negative value, on the other hand, implies that V2G would raise the amount paid per day which would not be appealing to participate in the given case.

This sensitivity analysis is done at a representative EV penetration level (e.g., 10%), so as to concentrate on owner-side economics without confounding high penetration on the overall system performance.

3.9.1 Sensitivity Analysis 1: Discharge Credit Factor (α)

The discharge credit factor α is the percentage of the existing electricity tariff at which the EV owners are compensated because of energy being discharged to the grid. Practically, this aspect indicates market regulations, utility motives, and rules regarding V2G compensation. As the rate of compensation is one of the most significant factors influencing the participation of the owners, its effect is explicitly discussed.

In this sensitivity study, the discharge credit factor α will be varied over a realistic range while keeping the time-of-use (TOU) tariff structure fixed. For each value of α, the daily net benefit to EV owners is computed as:

$$\varDelta C(\alpha) = C_{\text{uncontrolled}} - C_{\text{V2G}}(\alpha) \tag{27}$$

The less the discharge credit factor, the less the revenue obtained by the discharge at the peak periods but the battery degradation costs and charging costs show minimal difference. This causes a net benefit reduction gradually.

The neutral discharge credit factor, denoted by α^*, is defined as the value of α for which the net benefit becomes zero:

$$\Delta C(\alpha^*) = 0 \tag{28}$$

At this point, EV owners neither gain nor lose economically from participating in V2G. Values of α above α^* make V2G economically attractive, whereas values below α^* result in a net cost increase. Identifying this threshold provides important insights into the minimum compensation level required to sustain voluntary EV participation in V2G programs.

3.9.2 Sensitivity Analysis 2: Off-Peak Tariff Variation (Shoulder and Peak Fixed)

The second sensitivity analysis is to study how the off-peak electricity tariff would affect the economic attractiveness of V2G operation. Although V2G advantages mostly present themselves due to the discharging process during peak hours, the price of battery recharging during off-peak hours is a very important factor in establishing the net benefit.

In this analysis, the off-peak tariff p_{off} is varied over a practical range, while the shoulder and peak tariffs are fixed. The discharge credit factor α is also fixed at a representative value (e.g., $\alpha = 0.90$) to isolate the effect of off-peak price changes.

For each off-peak tariff value, the net benefit is calculated as:

$$\Delta C(p_{\mathrm{off}}) = C_{\mathrm{uncontrolled}}(p_{\mathrm{off}}) - C_{\mathrm{V2G}}(p_{\mathrm{off}}) \tag{29}$$

As the off-peak tariff increases, the cost of replenishing the energy discharged during peak periods rises. This progressively reduces the arbitrage margin between charging and discharging, especially when battery degradation costs are taken into account.

The neutral off-peak tariff, denoted by p^*_{off}, is defined as the tariff value at which:

$$\Delta C(p^*_{\mathrm{off}}) = 0 \tag{30}$$

This is the highest off-peak electricity rate at which V2G would be financially feasible to the EV owners under the specified tariff scheme, and degradation conditions. Onward of this point the marginal cost of charging is greater than the marginal revenue of discharging, which makes V2G participation economically unattractive.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Load Profile Flattening

This part examines how the Electric Vehicle (EV) integration affects the feeder load behavior by evaluating three operating conditions, which are base (non-EV) load, uncontrolled EV charging, and coordinated Vehicle-to-Grid (V2G) operation. The paper includes the actual 11 kV Baneshwor feeder and the IEEE-33 bus radial distribution system to present a full picture in terms of the difficulties and solutions related to the EV adoption operation.

4.1.1. Baneshwor Feeder Load Profile

Figure 8 shows how the daily load profiles of Baneshwor feeder vary under base load, uncontrolled EV charging, and V2G-controlled operation at the 15% EV penetration. The base load curve is the current feeder demand without inclusion of EV and indicates the general day to day consumption of the area. Although this base load already demonstrates morning and evening peaks, it does not exceed the working capacity of the feeder.

The charging of EVs without control could create a serious problem as it adds up to the already existing feeder peaks especially in the evening hours when the majority of the users come home and start charging. This impact of clustering causes sharp and intense surges in the demand of feeders that overloads transformers and feeder systems and risks overloading, higher losses, and decreased reliability.

V2G operated operation, in contrast, is a strategy of operation that schedules charging and discharging operation in order to flatten out the load profile. When the connected EVs are discharging power to the grid during peak demand periods, this amounts to shaving of the peaks of demand since the charging process is diverted to off-peak or low-demand periods. This synchronized operation minimizes evening peaks and fills demand valleys to maintain the feeder load within operational limits and near the desired reference level.

fThe effect of this has been well illustrated in the Baneshwor feeder case. The morning and evening peaks are already seen in the base load profile and the profile is within safe feeder capacity. As the EV charging is not controlled, the peak of the evening load grows significantly, increasing the load on operations. The load profile under V2G control is visually more flatter, and the size of the evening peak is much less because of peak shaving and valley filling.

On the whole, the comparison indicates that V2G operation makes EVs passive loads flexible distributed energy resources. This does not only balance the feeder usage during the day, but also enhances load balancing, and minimizes the operation stress on distribution infrastructure. The Baneshwor feeder therefore runs nearer to its reference limit with V2G control and it is a manifestation of the usefulness of coordination in charging and discharging policies on the power systems in the future.

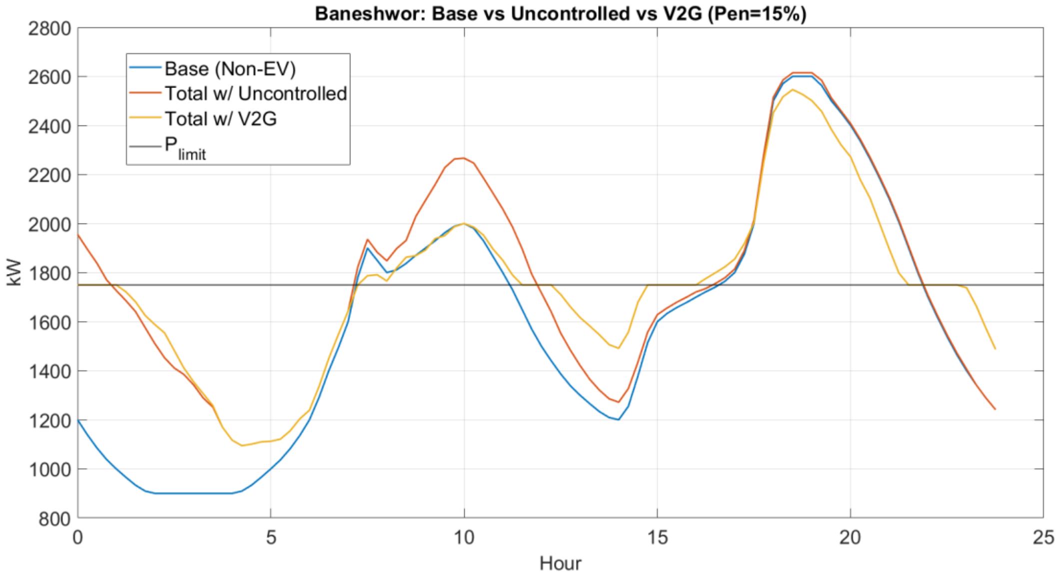

Figure 8: Feeder load profile V2G vs Uncontrolled(Baneshwor)

4.1.2. IEEE 33 Bus System Load Profile

Similar trends are observed in the IEEE-33 bus radial distribution system as shown in Figure 9. In uncontrolled charging, the system experiences a sharp increase of load during peak hours and becomes more pronounced at the higher EV penetration levels where concurrent charging increases the existing peaks by a significant factor. This shows how radial distribution networks are vulnerable to the adverse effects of incoordinated EV integration, especially in systems limited by feeder capacity.

With V2G controlled operation, the IEEE-33 bus system is much smoother in load profile. Peak conditions are considerably reduced because EVs inject energy into the grid during peak loads, which provides a sharp peak shaving effect. It does not only limit the extreme load excursions, but it improves the load factor of the system, and leads to more stable and balanced feeder operation. V2G scenario has less variance and more uniform distribution of the demand during the day than the example of the uncontrolled case. These IEEE-33 bus network results add to the perception that V2G benefits are not limited to specific feeder or geographic scope. Even in an integrated system of standardized benchmarks, coordinated charging and discharging of EVs can provide significant benefits in load smoothness and peak reduction. This not only validates the strength and transferability of the suggested V2G control strategy to various contexts of the distribution network.

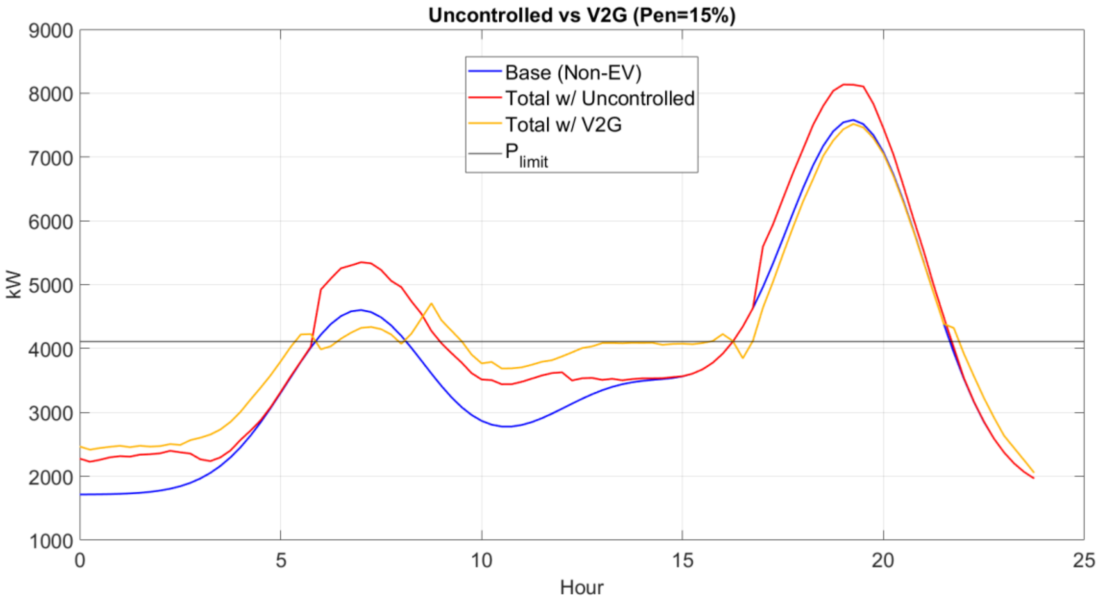

Figure 9: Feeder load profile V2G vs Uncontrolled(IEEE 33)

4.2 Impact of Increasing EV penetration

The impact of Electric Vehicle (EV) integration on distribution feeder performance becomes increasingly evident as EV penetration levels rise. To understand this effect, the Baneshwor feeder load profiles were analyzed under multiple EV penetration scenarios ranging from 10% to 20%, considering both uncontrolled charging and coordinated Vehicle-to-Grid (V2G) operation. The resulting load profiles provide important insights into how EV charging behavior influences peak demand, load volatility, and overall grid performance, and how V2G can effectively mitigate these impacts.

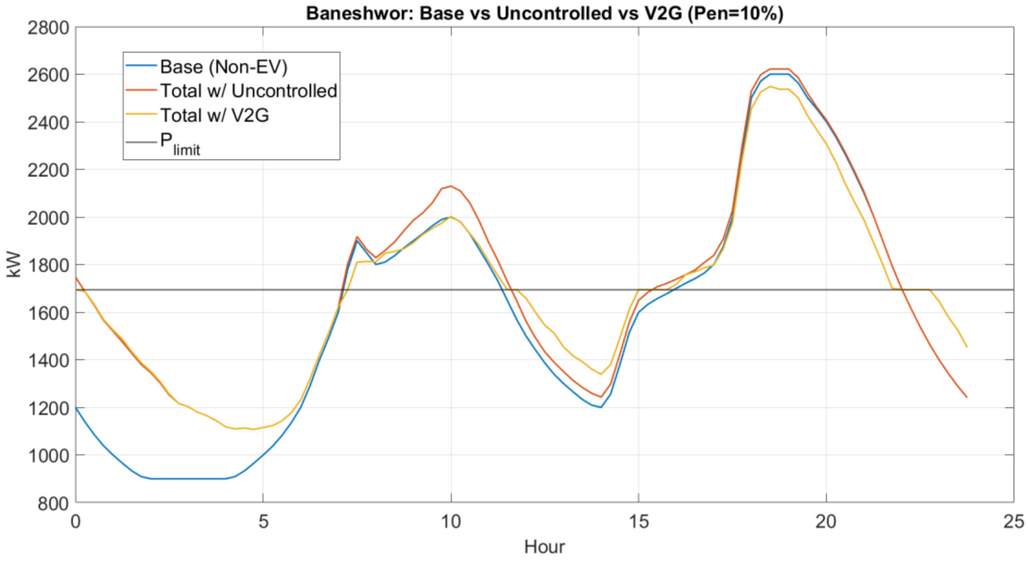

Figure 10: Feeder load profile - 10% Penetration(Baneshwor)

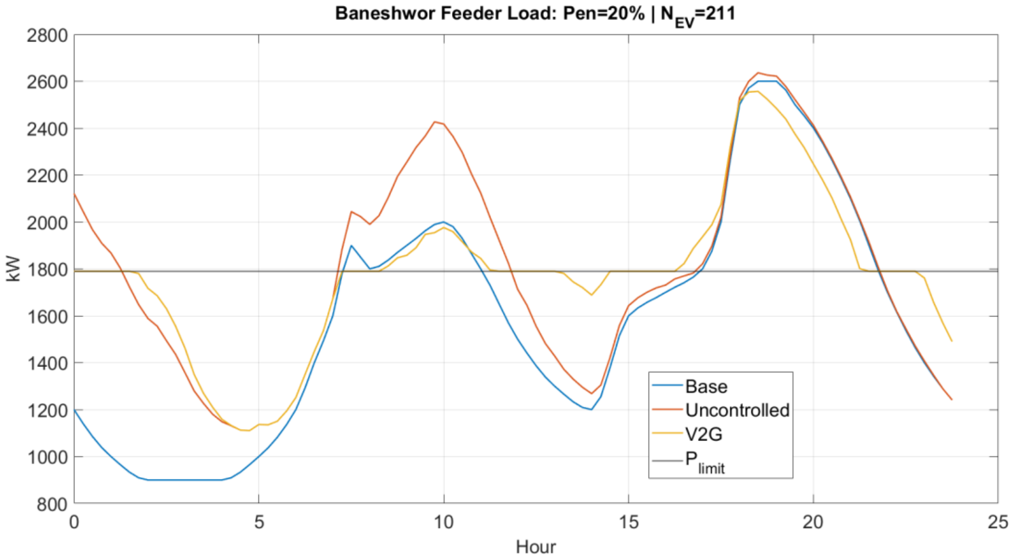

Figure 11: Feeder load profile - 20% Penetration(Baneshwor)

1. Amplification of Peak Load under Uncontrolled Charging

One of the most prominent findings across all EV penetration levels is the marked amplification of feeder peak load in the uncontrolled charging scenario. As penetration increases, more vehicles begin charging simultaneously especially during evening hours when users return home coinciding with the natural residential demand peak. This convergence produces sharp load spikes on the feeder and can rapidly exceed desired operational limits.

The EV demand is already adding visible increase to the evening peak at 10% penetration. The uncontrolled charging peak peaks considerably at 20, and it overcharges the feeder well at the point much higher than it was designed to reach. This tendency suggests that uncontrolled EV charging does not scale well with adoption: concentrating charging demand loads the system, increases the probability of transformer overloading, and exacerbates voltage control deviations as well as thermal bottlenecks.

From a distribution planning perspective, these results underscore that even moderate levels of EV adoption can create significant operational challenges if left unmanaged. Without the implementation of effective charging control strategies, increased EV uptake could require costly infrastructure upgrades simply to maintain reliable network performance.

2. Consistent Load Smoothing with V2G Integration

Contrary to the uncontrolled scenario, the V2G-controlled scenario always yields a more balanced and smooth load profile with respect to all the penetration levels. Whether EV penetration is 10% or even as large as 20%, the organized operation of V2G curbs growth of peak demand and maintains the feeder load nearer to the reference operating point.

This behavior is achieved by intelligently scheduling EV charging during low-demand periods and enabling controlled discharging during peak hours. As a result, the evening peak is effectively shaved, while the midday and overnight valleys are partially filled. The feeder load curve under V2G therefore exhibits reduced extremes and improved uniformity throughout the day.

Importantly, the effectiveness of V2G does not diminish as penetration increases. Instead, the ability of EVs to collectively support the grid improves with higher participation, demonstrating that V2G is not only effective at low penetration levels but also scalable for future scenarios with widespread EV adoption.

3. Enhanced Peak Shaving and Valley Filling at Higher Penetration Levels

Another key observation is that the peak shaving and valley filling effects of V2G become more pronounced as EV penetration increases. At lower penetration levels, the impact of V2G on peak reduction is noticeable but relatively modest. However, as more EVs participate in coordinated charging and discharging, their combined storage capacity grows, allowing for greater flexibility in load shaping.

At higher penetration levels, the V2G-controlled load profile shows significantly reduced peak magnitudes and elevated off-peak demand. This indicates that EVs are effectively absorbing excess energy during low-load periods and supplying energy back to the grid during peak demand. The result is a flatter daily load curve with improved load factor and more efficient utilization of feeder capacity.

This behavior demonstrates an important advantage of V2G systems: their effectiveness increases with scale. As EV adoption expands, V2G becomes an increasingly powerful tool for managing demand, reducing the need for peaking generation, and deferring network upgrades.

4. Reduction in Load Volatility and Improved Grid Stability

Load volatility is another critical aspect influenced by EV penetration. In the uncontrolled charging case, higher penetration leads to increased fluctuations in feeder load throughout the day. These fluctuations introduce operational uncertainty and make real-time system management more challenging for utilities.

Under V2G operation, however, load volatility is significantly reduced across all penetration levels. The feeder load transitions more smoothly between time periods, avoiding abrupt changes associated with mass charging or sudden load drops. This smoothing effect enhances grid stability, reduces mechanical and thermal stress on equipment, and improves the overall reliability of the distribution system.

The reduction in volatility is particularly important for urban feeders such as Baneshwor, where demand variability is already high. By using EVs as distributed energy storage resources, V2G provides an effective mechanism to absorb and release energy in response to system needs, thereby strengthening the resilience of the grid.

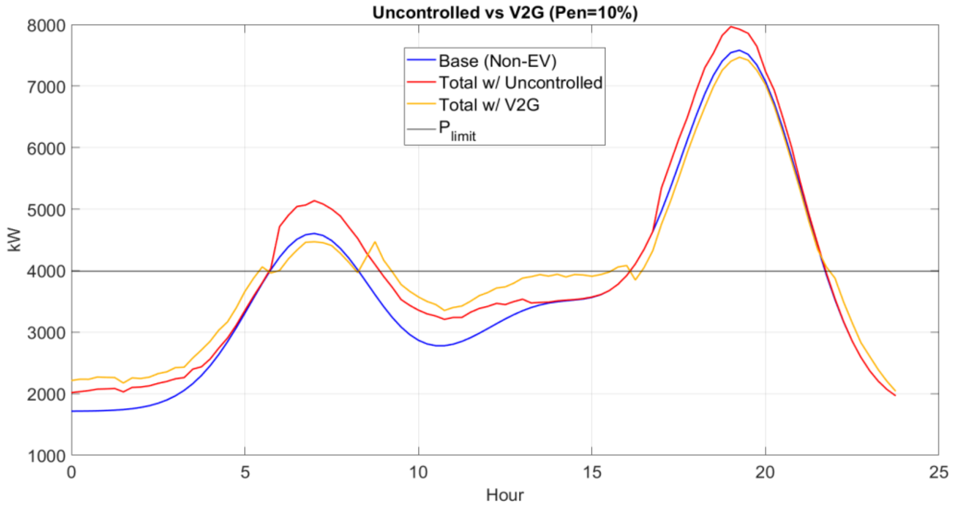

Figure 12: Feeder load profile -10% Penetration(IEEE 33)

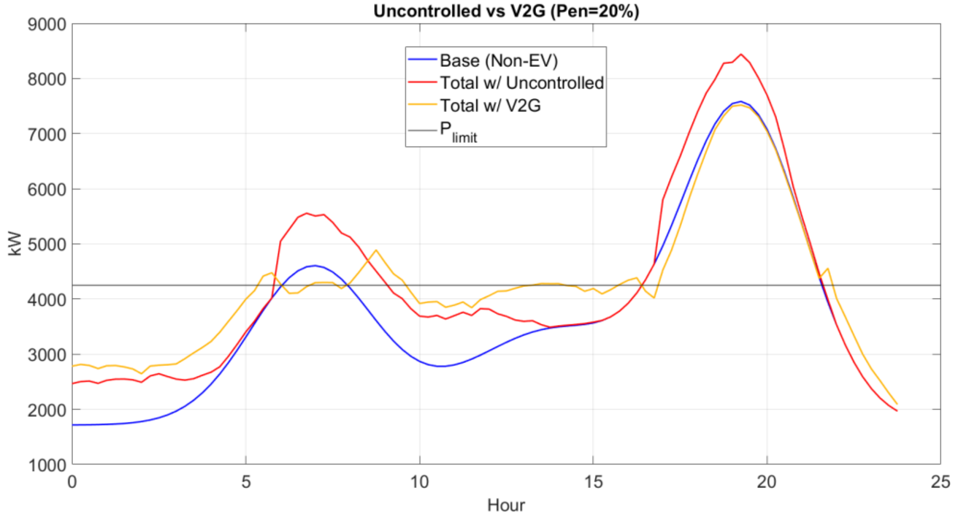

Figure 13: Feeder load profile - 20% Penetration(IEEE 33)

5. Implications for Future Grid Planning

The results clearly indicate that increasing EV penetration without coordinated control poses serious challenges for distribution networks. However, when combined with V2G-based control strategies, higher EV penetration can be accommodated without compromising feeder performance. In fact, V2G enables EVs to transition from being a source of stress to becoming an active asset for grid support.

For developing power systems like Nepal, where distribution infrastructure upgrades are costly and time consuming, these findings are particularly significant. Coordinated V2G operation offers a practical and scalable solution to manage the growing EV load while maintaining grid reliability and operational efficiency.

4.3 Cost Benefits to EV Owners

Figure 14 shows the daily costs items of EV owners at a 20 % penetration in the uncontrolled charging case and with the coordinated charging case of Vehicle-to-Grid (V2G). The cost factors would be the charging cost, discharge credit, battery degradation cost and the cost per day. This analysis gives a better insight into the impact of V2G participation on the economics of EV ownership in general.

1. Charging Cost Comparison

Contrary to the uncontrolled charging case scenario, the V2G-controlled scenario may end up with a somewhat increase in the overall charging cost. This might not make sense at first sight but it is a direct result of V2G functioning.

Uncontrolled charging uses the EVs that start charging as soon as they arrive and cease charging as soon as the needed state of charge (SOC) is attained, that is, the amount of energy consumed only leads to mobility. In comparison, V2G will enable the EVs to release energy to the grid when peak periods occur and then they will be required to recharge once more to ensure that they meet the target SOC by the time of departure. This cyclic charging and discharging causes an increment to the total energy throughput hence more electricity is used throughout the day.

Although V2G charging is favored with regards to scheduling within the off-peak tariff to reduce costs, the extra energy load demanded during recharging may result in the total charging expense of V2G being marginally higher than in the uncontrolled level of charging. The trend can be observed in Figure 14, where the price bar of charging of the V2G case is slightly a bit higher than that of the uncontrolled charging.

2. Impact of Discharge Credits

One of the characteristics of the V2G situation is the presence of discharge credits, which are completely lacking in the uncontrolled charging scenario. EVs that work under V2G during peak demand periods release energy back to the grid and are paid money depending on the current peak tariff and discharge credit factor.

As shown in Figure 14, the discharge credit is a major component of negative costs. This revenue is important to balance the increased cost of charge related to the V2G operation. Effectively, the owners of EV are paid on the basis of offering meaningful peak-time energy assistance to the grid, making the EV batteries a revenue generator and not a liability.

3. Battery Degradation Cost

When comparing the costs of battery degradation in a V2G operation, an additional cost is also added by the presence of extra charging and discharging cycles. The simplified linear cost per unit of battery energy is used to model battery degradation in this study. As it can be predicted, the degradation cost is greater in the V2G scenario than when charging is uncontrolled, as it implies that the battery experiences an extra cycling.

The amount of the degradation cost, however, is quite small compared to the discharge credit and the charging cost. This implies that, assuming the degradation rate, battery degradation is not the main economic indicator of the V2G participation.

4. Net Daily Cost and Economic Interpretation

The overall daily cost of EV owners operating under V2G is reduced compared to uncontrolled charging when all the elements of costs are summed up even though the charging and degradation costs are higher. The amount of revenue generated by the discharge credits is more than the extra amount of energy paid and the wear of the battery.

This finding underscores a major implication of the research, which is the economic advantage of V2G is not determined by the decreased energy of charging, but rather by time-of-use tariff energy arbitrage. EV drivers are successful in buying electricity when the price is low and selling some of it back to the grid when the price is high and earning net savings on a day-by-day basis.

In general, the analysis of costs shows that V2G participation may also be economically viable to EV owners when further charges and battery degradation are considered. This supports the observational viability of V2G as a demand-side approach of management that matches the grid level incentives with individual-level monetary incentives, especially in systems with high levels of peak and off-peak price variations.

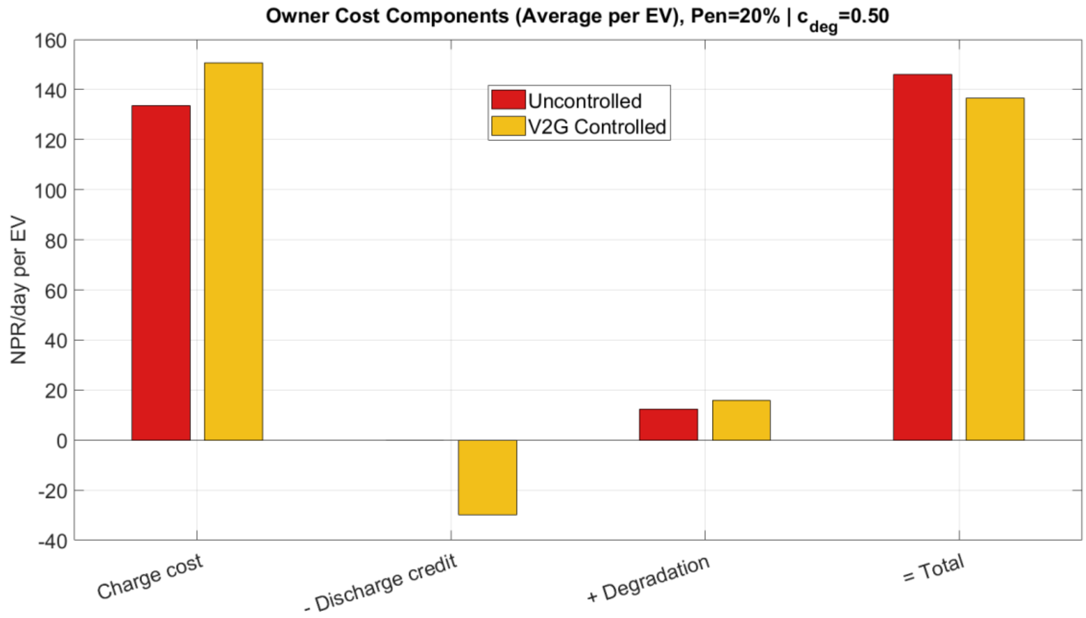

Figure 14: Total owner's cost uncontrolled vs V2G

4.4 Performance Indicators

4.4.1 Feeder Peak Load Vs EV Penetration

Under two operating conditions: uncontrolled charging and coordinated Vehicle-to-Grid (V2G) operation, Figure 15 shows the changes in peak feeder load as a function of Electric Vehicle (EV) penetration. Such a comparison offers valuable information on the impact of large scale EV going to large magnitude distributions stress and the effectiveness of V2G in alleviating stress.

Under uncontrolled charging condition, the feeder peak load grows nearly inversely with the EV penetration. With additional EVs attached to the system, more vehicles start to charge at the same time, especially at the evening peak hours when residential demand is already high. Directly proportional to this clustering of the charging behavior is a glaring increase in the maximum load of the feeder. As the penetration level rises, the peak demand grows significantly, which means that the distribution feeder gets more and more stressed, becoming more and more vulnerable to overloading. The influence of this trend is a major restriction of the uncontrolled EV charging, which increases the peak demand instead of spreading it more uniform over the day.

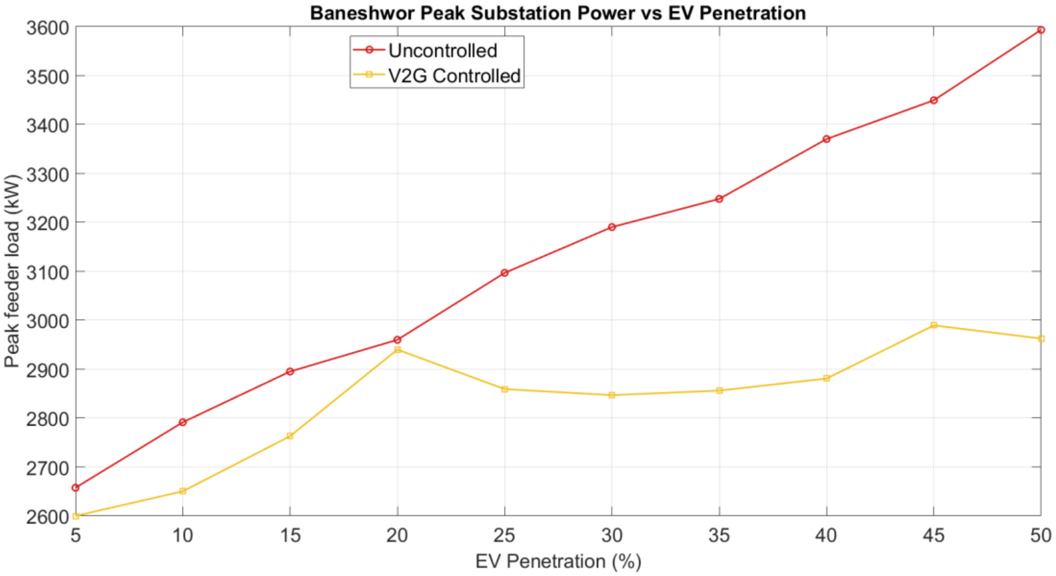

Figure 15: Feeder peak load vs EV penetration(Baneshwor)

However, the situation with V2G control is characterized by a significantly different behavior. Although the peak load continues to vary somewhat with the increasing EV penetration, its increase rate is much lower than the uncontrolled case. The coordinated V2G approach can also have EVs release energy to the grid during peak energy demand effectively offsetting the extra charge brought about by EV charging. Consequently, the peak feeder load will be lower at all levels of penetration. The peak load of V2G-controlled is significantly lower than the peak load of the uncontrolled case even at high EV penetration, which indicates that V2G can decouple the increase in the peak demand with EV adoption.

The other notable observation made of the figure is that the difference between the uncontrolled and V2G peak loads expands with increase in EV penetration. This means that the advantages of V2G are not only retained but increased with the increase in the level of penetration. The capacity to store energy that can be fed into the grid grows, as more EVs are engaged in coordinated charging and discharging, to better serve the system in shaving peaks and provide a more efficient way to manage demand.Overall, this analysis confirms that uncontrolled EV charging poses a serious challenge to distribution system operation as EV adoption rises, primarily through rapid peak load escalation. In contrast, V2G operation provides a scalable and effective mitigation mechanism by leveraging EV batteries as distributed energy resources. By reducing peak feeder demand and limiting its growth with increasing EV penetration, V2G contributes directly to improved grid reliability, reduced infrastructure stress, and deferred network reinforcement. These findings underscore the importance of coordinated EV integration strategies for future urban distribution systems, particularly in rapidly electrifying environments such as Kathmandu Valley.

4.4.2 Load factor Vs EV Penetration

One of the indicators of efficient distribution of electrical demand with time is the load factor. An increased load factor would mean that the feeder spends a larger percentage of the day at its average load and this means a more stable demand as well as asset utilization and efficiency of the system. Figure 16 demonstrates that the load factor of the Baneshwor feeder changes with the EV penetration at the uncontrolled charging and V2G-controlled operation.

When the charging is uncontrolled, the load factor can be seen to have a slow decrease with EV penetration. This pattern indicates the growing unequal demand distribution due to the uncoordinated EV charging pattern. The charging activities are likely to be concentrated at certain times of the day as more EVs are rolled out with the existing pattern of charging during the evening hours when there is already a high demand on residential power. This causes a sharper peak of demand with other periods underutilized hence increasing the difference between the average and the peak load. The falling load factor signifies increased volatility and poor operating efficiency of the load because what the feeder is supposed to do is to handle high peak demand that is only being experienced over only a short period of time.

Conversely, the scenario under V2G control shows a definite increase in load factor as the numbers of EVs increase. V2G is also active in terms of redistribution of energy demand throughout the day, which is achieved by coordinated charging and discharging. EVs absorb energy when the demand is low and inject it back to the grid when the demand peaks and this helps to reduce peak demand and increase the average load level. It results in a more flattened load profile and an increased load factor and suggests that there is more efficient utilization of the feeder and other infrastructure.

A notable fact about the figure is that the advantages of V2G are more at higher rates of penetration. Where the load factor when charging under uncontrolled conditions becomes increasingly worse due to the adoption of EVs, the case of V2G-controlled charging remains in an upward trend. This indicates how scalable V2G is as a demand management approach because small groups of EVs store less energy and have less flexibility to offer grid operation, whereas larger groups offer higher capacity and more flexibility.

In general, the load factor analysis supports the reference that uncontrolled EV charging reduces the efficiency of the distribution system with the rise of EV penetration. By contrast, the V2G integration, in addition to alleviating these adverse effects, actually increases the efficiency of the feeder by increasing load uniformity and minimizing the difference between peaks and average loads. This gain in load factor is directly converted into less stress on the network elements, more efficient use of available resources, and less infrastructure fortification, V2G is a technically appealing solution towards the task of managing high EV penetration in urban distribution systems.

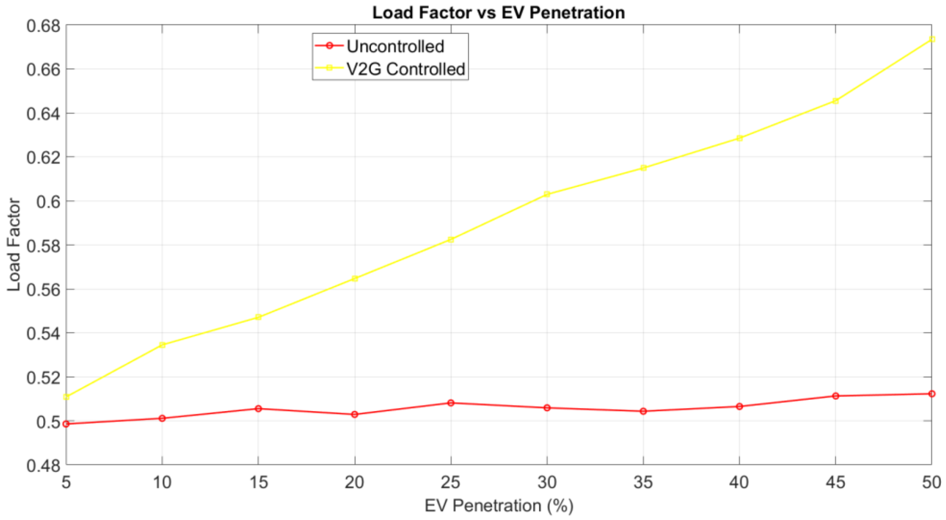

Figure 16: Load factor vs EV penetration(Baneshwor)

4.4.3 Flattening Index

This work uses the Flattening Index (FI) to evaluate the effectiveness of Vehicle-to-Grid (V2G) in relation to the uncontrolled EV charging, in terms of flattening the daily feeder load profile. In contrast to peak load or load factor, which only measures particular areas of system performance, the flattening index is a more comprehensive measure of the variability of load in a system by directly showing the reduction in variation of load across the entire operating horizon.

The change in flattening index with an increase in EV penetration in the Baneshwor feeder and IEEE 33-bus distribution system is indicated in Figure 17 and 18, respectively. A consistent upward trend in both systems in the case of increased EV penetration can be seen in terms of FI. This tendency implies that the load profile is flatter as a bigger percentage of EVs are involved in coordinated V2G operation.

The flattening index is not very high at low levels of EV penetration. This is not surprising, since the few EVs offer a small degree of flexibility in the redistribution of load. However, V2G is not only limited by the small amount of available battery capacity but also means that some peak shaving and valley filling is possible, nevertheless. Subsequently, the daily load curve does still have observable peaks and troughs.

The flattening index of each network increases as the EV penetration increases. This growth is an indication of the higher capacity of V2G system to actively manipulate the load profile. As EVs become increasingly connected and engaged, a greater aggregate battery capacity is made accessible to take energy in during periods of low-demand and provide power during times of peak demand. This synchronized action minimizes the size of the fluctuations of loads and causes a more evenly distributed demand over the day.

This increase in the flattening index is also strong especially at moderate-high levels of penetration. Under such circumstances, V2G discharging in peak periods will considerably decrease the level of load peaks whereas off-peak discharging will load the valleys better. This two-fold effect creates a smoother and more stable load curve as indicated by an increase in the values of FI. Notably, this enhancement is made without affecting the mobility requirements of EVs, since SOC constraints and target SOC at departure are controlled in the framework of the control.

The same tendency can be observed on the Baneshwor feeder and the IEEE 33-bus, which proves that the advantages of the load flattening by V2G are not specific to the system. Although the networks can have variances in terms of network size, characteristics of loading and demand at base level, the flattening index is always enhanced with EV penetration effectiveness under V2G control. This attests to the soundness and applicability of the proposed V2G model to various radial networks of distribution.

On the whole, the findings demonstrate the presence of the flattening index growth with EV penetration during the coordinated working of V2G, which indicates the scalability of V2G as a load management approach. With the ongoing increase in EVs, V2G is increasingly useful in reducing the demand changes, a better fitment of loads, and increasing the operational stability of distribution systems. These results confirm the importance of V2G as an enabling technology in future smart grids, especially in urban feeders where EV penetration is increasing.

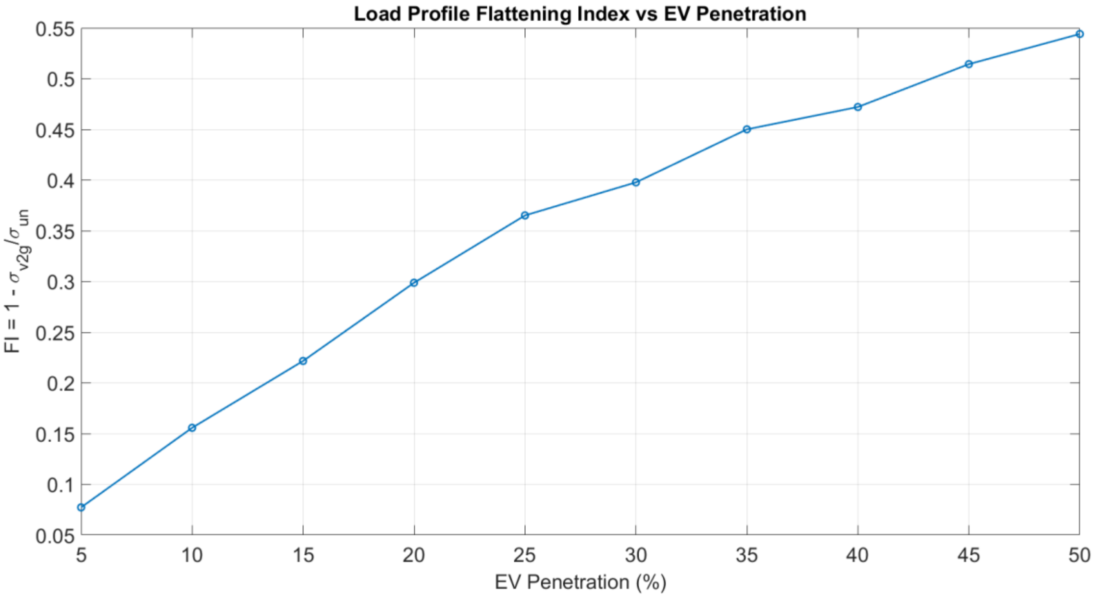

Figure 17: Load profile flattening index (Baneshwor)

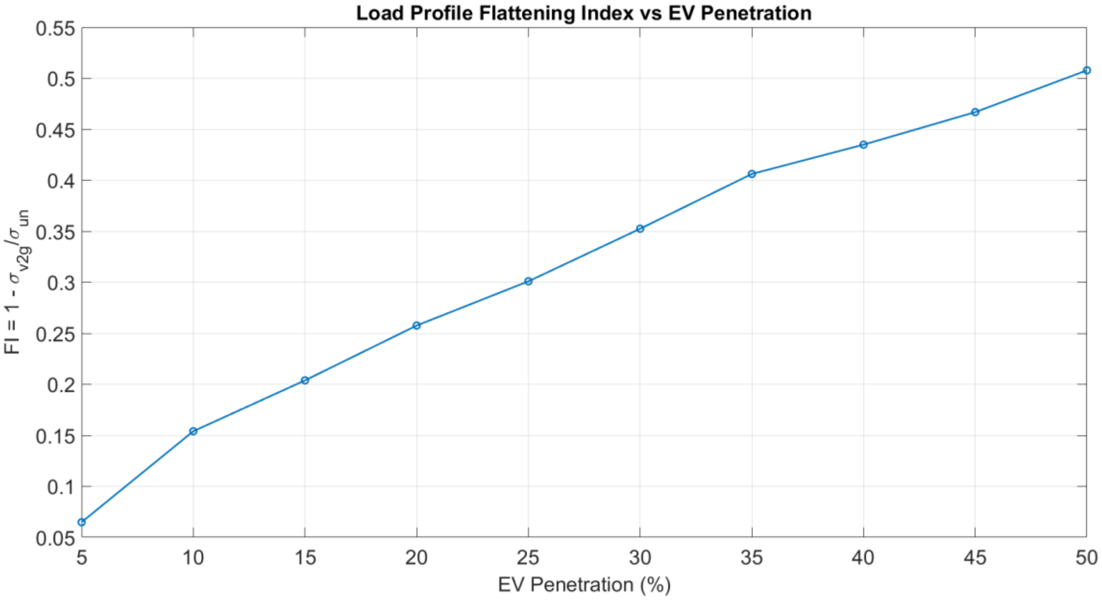

Figure 18: Load profile flattening index(IEEE 33)

4.4.4 Average daily charging cost

Figures 19 and 20 show how the average daily cost of energy per electric vehicle changes with two operating conditions, including both uncontrolled charging and coordinated V2G operation, over various EV penetration levels. The comparison allows gaining deep insights into how the behavior of charging and control strategies will affect the economic performance of EV owners as the electric mobility increases.

The uncontrolled charging case means that EVs will be charged as soon as they are connected, which is usually at night time when the demand for residential electricity is already high. With more EVs, more vehicles are charged at the same time at these peak hours. This means that there will be increased exposure to peak and shoulder tariffs resulting in the overall increase of the average daily charging cost per EV. Even though it is seen that there is a certain variation because of the difference in arrival time and base load conditions, the overall tendency is that uncontrolled charging would be more costly as EV usage increases. This shows the inefficiency in the uncoordinated charging where the convenience of the user prevails over cost and system considerations.

Conversely, the V2G-managed case shows lower average net cost per EV in each of the penetration levels. In V2G, charging and discharging are synchronized so as to meet mobility needs and react to time-of-use price information. EVs charge mostly during off-peak times when the price of electricity is low and can release the energy to the grid during peak times and receive discharge credits. Notably, the end-state-of-charge within departure conditions in this research is kept constant in either uncontrolled or V2G scenario. Consequently, EVs that take part in V2G can be slightly cheaper to charge grossly than in the case of uncontrollability because the energy released at peak times will have to be restored.

This is the reason why the charging cost element in itself may be increased in the case of V2G than on the uncontrolled scenario. But considering discharge credits and battery degradation expenses the net daily cost is still less in case of V2G players. The price of charging during the high-price periods is well compensated by the discharging revenue and the extra cost of charging and the cost of degradation. This is a balance, and this net economic advantage is that EV owners involved in V2G have, despite potentially cycling their batteries more actively.

The economic value of V2G does not decrease with a growth in EV penetration but in certain instances, it is even stronger. Although increased penetration requires increased competition in low-cost charging window and total energy throughput, the coordinated mechanism of scheduling makes EVs still consider price differentials effectively. This shows that not onlyV2G is cost-saving at low penetration levels but also is scalable with the increase in EV adoption rates.

Altogether, the findings confirm that the participation of V2G has definite economic benefit compared to uncontrolled charging, not because it decreases the energy consumption via charging, but because it is a strategic shift of energy exchange over time. V2G will turn EVs into passive loads by charging at the time of low tariffs and charging during the peak to realize the value of energy discharge. The result supports the feasibility of V2G as an affordable method to the EV owners specifically in urban distribution networks when there are time-dependent electricity rates and where EV proliferation is increasing.

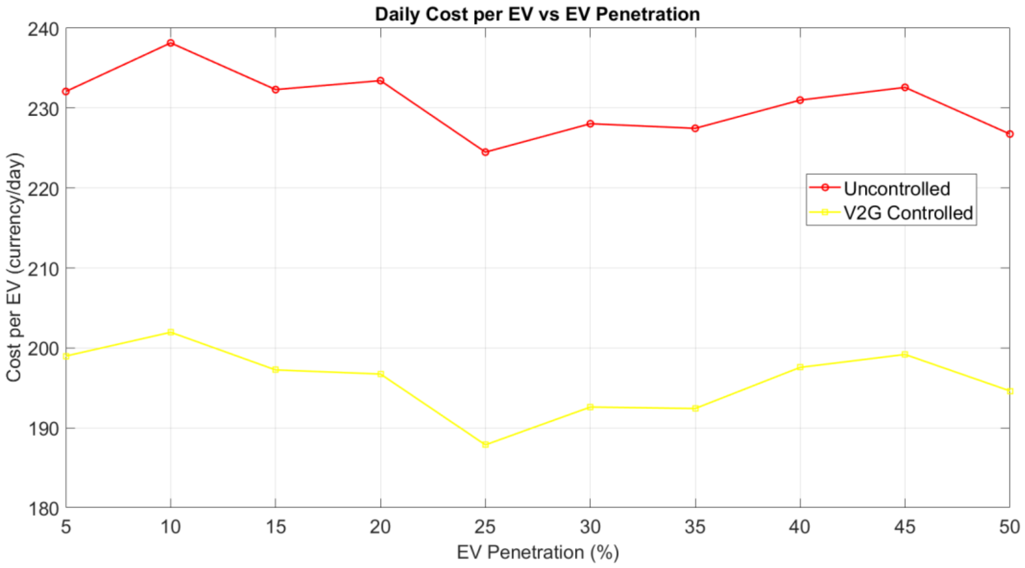

Figure 19: Average daily charging cost vs EV penetration(Baneshwor)

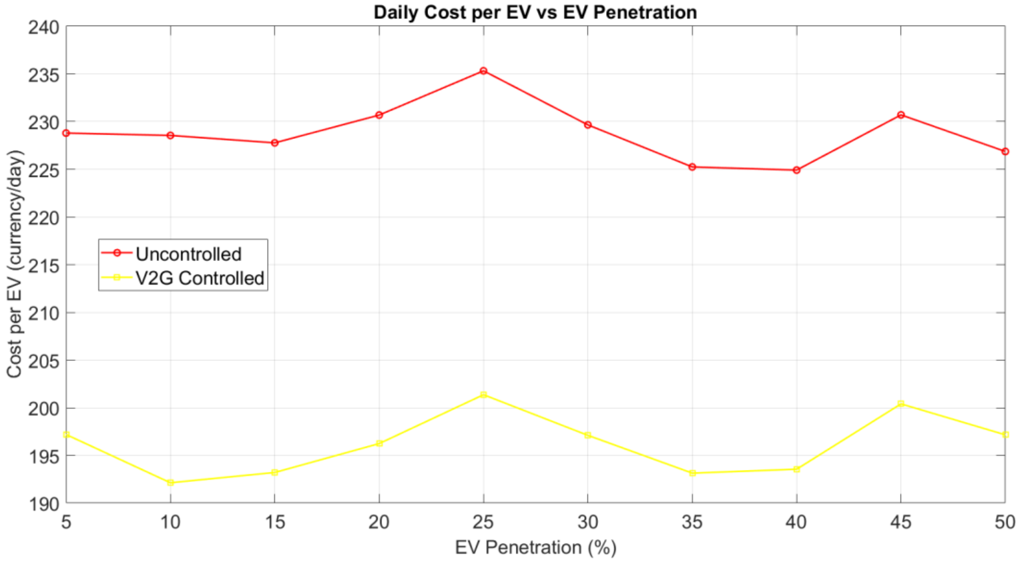

Figure 20: Average daily charging cost vs EV penetration(IEEE 33)

4.4.5 Percentage daily cost savings

Figures 21 and 22 show the percent savings in daily costs by the owners of Electric Vehicles (EV) operating within Vehicle-to-Grid (V2G) and compared to the uncontrolled scenario of charging when EV penetration varies. The indicator offers a clear indication of the relative economic benefit of V2G participation and allows to comprehend the way this benefits vary with the growth of EV adoption.

At the early stages of EV penetration, the daily cost savings in the form of V2G is present but with moderately low percentages. This is mainly due to the fact that when there are less vehicles that can be charged and discharged the overall sum of energy that is exchanged between EVs and the grid is minimal. The fact that EVs still have access to off-peak charging and limited peak-time discharge does not mean that the system impact is not limited due to the smaller number of EVs.

The percentage daily cost savings increase as the EV penetration increases. The more EVs enrolled in the V2G program, the higher amount of energy may be released during peak demand rates and moved to the off-peak periods of charge. This improved coordination enables EV owners to enjoy better benefits of time-of-use (TOU) prices. The findings indicate that the V2G provides the best relative cost-saving at moderate levels of penetration rates because the relationship between the discharge capacity available and the flexibility of charging is the best. At this range, EV owners are able to offset a large portion of their charging costs in the form of discharge credits whilst retaining their necessary state-of-charge to be mobile.

The proportion of daily cost savings starts to slightly decrease in percentage at a higher EV penetration. Such a trend is not a signal of loss of economic advantage but it is more of a saturation effect in the system. The greater the number of EVs involved in V2G, the higher the number of available opportunities of peak-time discharge to be shared between more vehicles. This leads to a reduction in the marginal benefit per EV, although the levels of benefits on a system-wide scale are large. Moreover, more charging is done to achieve target SOC levels and more aggregate battery throughput leads to a minor decrease in relative savings at extremely high penetration levels.

Although this decrease is present, the results all indicate that V2G participation can offer substantial economic benefits at all penetration levels analysed. The amount of daily saved percentage is in a realistic range, usually 10-20% per EV, which proves that V2G is able to provide sustainable financial incentives to EV owners. This results indicate that V2G is not just useful in the operation of grids but also cost-effective to the user even as the adoption of EV grows.

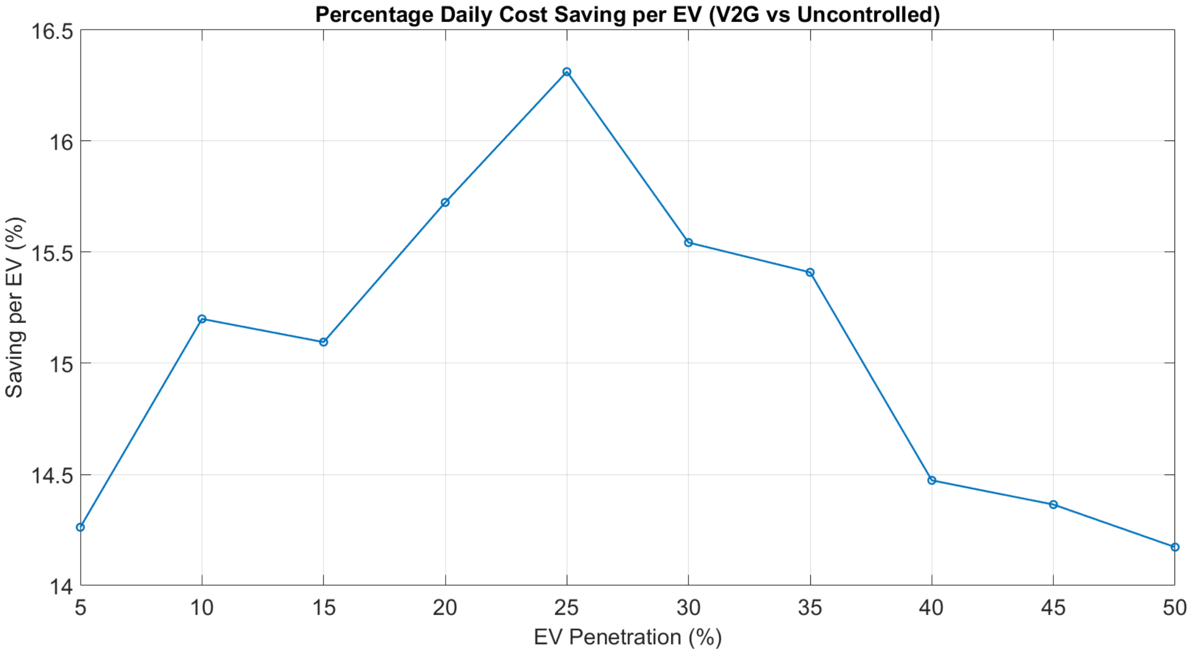

Figure 21: Percentage daily cost saving vs EV penetration(Baneshwor)

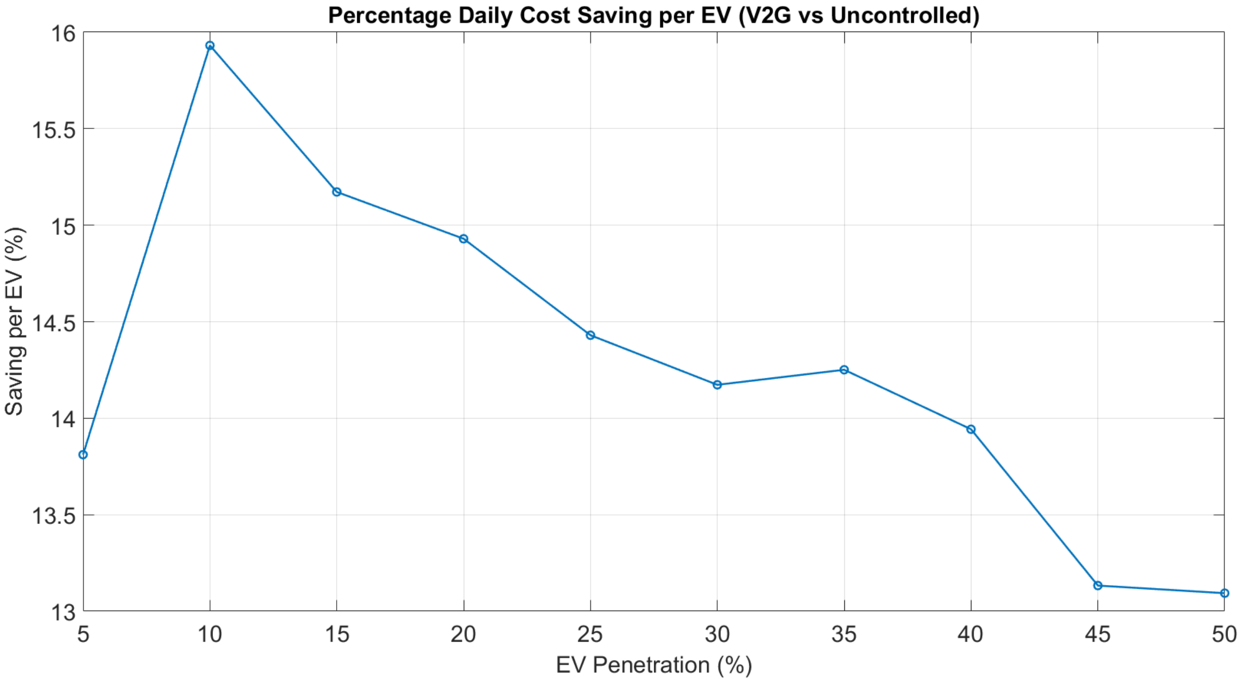

Figure 22: Percentage daily cost saving vs EV penetration(IEEE 33)

Overall, the percentage daily cost savings analysis reinforces the viability of V2G as a long-term solution for integrating large numbers of EVs into urban distribution networks. While individual savings may peak at moderate penetration levels, the continued presence of positive savings across all scenarios supports the role of V2G as a balanced and economically sustainable approach for future smart grid deployment.

4.5 Sensitivity 1: Discharge Credit Factor α

Figure 23 illustrates the sensitivity of the EV owner net benefit (ΔC) with respect to the discharge credit factor, α. The discharge credit factor represents the fraction of the applicable electricity tariff that EV owners receive as compensation when they discharge energy back to the grid during peak demand periods. The resulting curve shows a clear and monotonic increase in ΔC as α increases, indicating a strong and direct relationship between discharge compensation and the economic attractiveness of V2G participation.

The analysis identifies a distinct neutral threshold at approximately
$\alpha^* \approx 0.84$,
where the net daily benefit becomes zero.

For values of α greater than 0.84, the net benefit ΔC remains positive, indicating that V2G operation is economically advantageous for EV owners. In this region, the discharge revenue earned during peak periods is sufficient to offset the combined costs associated with energy losses, additional charging required to restore the battery state of charge, and battery degradation due to increased throughput.

On the other hand, the net benefit becomes negative when falls is below 0.84. In such circumstances, the amount of compensation that is paid to give out discharged energy is not sufficient to offset the expenses that were spent on charging more and wearing off the battery. This means that under the V2G operation, EV owners would incur a more expensive daily cost than in uncontrolled charging and V2G participation would be economically unattractive.

This action is in line with the owner cost model structure. The discharge revenue term is proportional to a, and it is directly proportional to financial gains of V2G operation. Contrastingly, the cost of battery degradation and efficiency loss do not significantly depend on the rate of compensation and have to be incurred each time there is a charging and discharging process. Besides this, the energy released during peak hours will have to be restored to arrive at the target state of charge that is necessary at departure which further adds to charging costs. Thus, there is a minimum discharge credit level that is needed to be overcame to obtain positive net returns.

In practical sense, the threshold a identified a valuable guideline in designing V2G programs and to design tariffs. Provided that aggregators or utilities pay discharge compensation lower than about 84% of the relevant TOU rate, EV owners cannot be expected to receive the economic returns with consistency under the operating assumptions assumed in this paper. Conversely, a compensation higher than this level provides a good financial motivation to participate and align the interests of EV owners to create grid support goals.

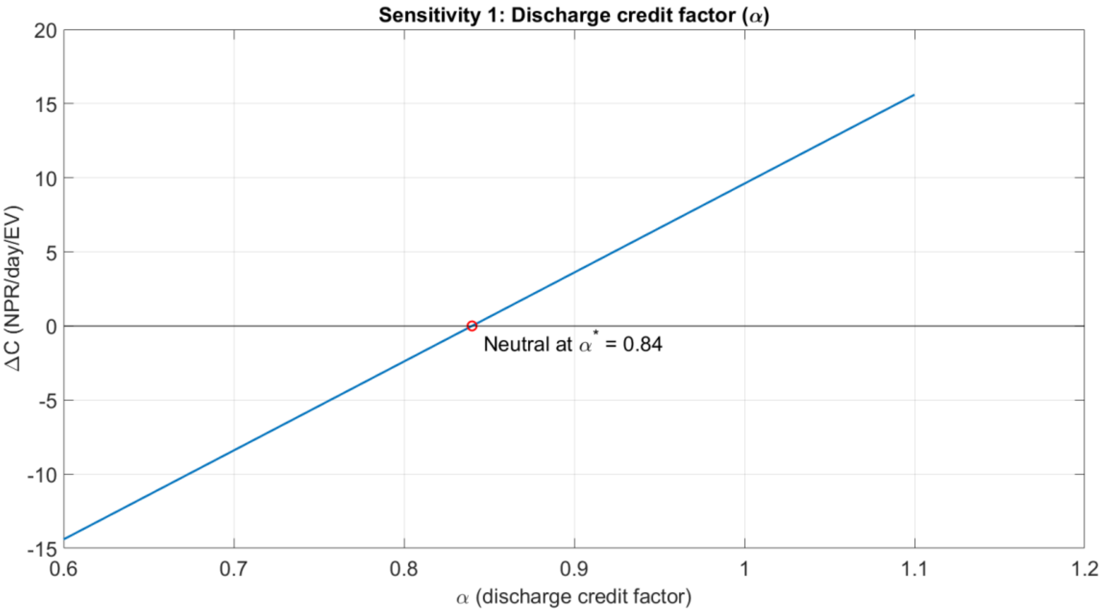

Figure 23: Owner net benefit VS Discharge credit factor

In general, the sensitivity analysis shows that discharge compensation policy is extremely important as it determines the economic feasibility of V2G. It highlights that in as much as V2G can deliver significant benefits at the system level, it is important to note that proper incentive schemes are necessary in order to guarantee long term and voluntary participation by EV owners.

4.6 Sensitivity 2: Off-peak Tariff p_{off}

Figure 24 presents the sensitivity of the EV owner net benefit (ΔC) with respect to variations in the off-peak electricity tariff, while keeping the peak and shoulder tariffs fixed and the discharge credit factor constant at $\alpha = 0.90$. The resulting curve shows a clear and monotonic decrease in ΔC as the off-peak tariff increases, indicating that higher valley charging prices progressively erode the economic advantage of V2G participation.

The analysis identifies a distinct neutral off-peak tariff at approximately
$p^*_{off} \approx 6.83$ NPR/kWh,
which represents the break-even condition for EV owners.
When the off-peak tariff remains below 6.83 NPR/kWh, the net benefit ΔC is positive, meaning that V2G operation is economically attractive. In this region, EVs are able to recharge at sufficiently low cost during valley hours, while earning relatively high compensation for discharging energy during peak periods. This price differential allows EV owners to recover charging costs, compensate for battery degradation, and still achieve net daily savings.

The net benefit however becomes negative when the off-peak tariff is beyond 6.83 NPR/kWh. In this case, energy replenishment cost is high due to the release of high energy during peak hours. Peak-period discharge revenue will stay at the same level but due to the increasing cost of charging at the valley, which is inevitable and the losses due to battery degradation and round-trip efficiency, the overall economic margin of V2G operation is decreased. At some point, the refund amount of recharging will exceed the amount refunded on discharging, and thus V2G participation will not be cost-effective to the owners of EVs.

This tendency indicates a basic economic principle of V2G systems: V2G profitability lies not in the high peak prices only but also in the necessary low off-peak prices. Discharge-and-recharge cycle can only be applicable where price spread between valley and peak periods is elevated. When the off-peak tariff is near shoulder or peak price rates this price arbitrage opportunity decreases quickly even where the discharge credit factor is relatively high.

The discovered neutral off-peak tariff is a valuable design indicator under practical and policy consideration. It shows that V2G programs cannot be based on high peak tariffs or generous discharge compensations only. They should also however make sure that off peak electricity rates are also kept low to maintain the economic motive of owning an EV. In the absence of a clearly outlined and discounted enough valley period, V2G participation can reduce, despite the possible benefit at the system level.

Comprehensively, this sensitivity analysis implies that tariff structure is one of the most important issues that can determine the success of V2G integration. A price scheme based on time-of-use, with a substantial difference between off-peak and peak rate is a crucial element in supporting the continued EV owner involvement, along with the long-term V2G feasibility.

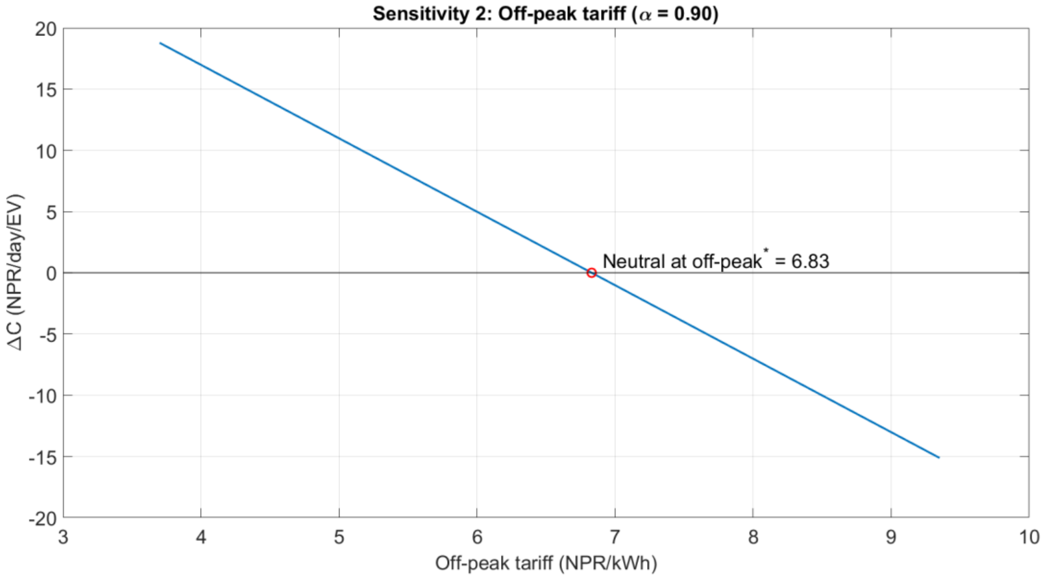

Figure 24: Owner Net Benefit VS Off peak tariff

CHAPTER 5: CONCLUSION

This research offers an analytical and practical evaluation of the Vehicle-to-Grid (V2G) technology as a feasible approach to overcoming the operational and economical difficulties associated with the growing use of electric vehicles (EV) in the distribution systems of the radial design. With the increase in EV numbers, uncontrolled charging becomes a major source of congestion to the current networks especially in cities where the feeders may be working at full capacity. The research reveals that achieved coordination of V2G operation can be effective in eliminating these challenges, and it can provide real economic value to the owners of EVs. One of the key culminating results of this effort is the significant enhancement of the profiles of feeder loads by use of V2G coordination. It was also determined that uncontrolled EV charging enhances evening peaks creating sharp load spikes that can increase system loading, losses and the risk of congestion. On the other hand, the suggested V2G control approach allows EVs to charge during off-peak times and discharge during peak times, which results in a far smoother daily load curve. The evidence of the ability of V2G to improve grid stability and operation efficiency is shown by consistent increases in technical performance measures such as reduced peak load, higher load factor, and increased flattening index. Notably, the economic worth of V2G participation to the EV owners is also highlighted in the study. In a time-of-use (TOU) tariff, co-ordinated pricing during the periods when the energy is not used, plus controlled discharging during the periods of high prices, the net day-to-day energy payments are lowered. Despite consideration of battery degradation through an oversimplified linear cost model, it can be seen that there are consistent daily cost reductions of around 10-20 % depending on the level of EV penetration. Such savings reduce the fear of fluctuating electricity costs and battery lifetime, thereby enhancing the overall economic case of EVs owners and reinforcing the incentives to V2G participation. The study also brings out scalability of V2G benefits with rising EV adoption. Although there are immediate benefits in load levelling already at low penetration, the beneficial effect of V2G increases with the increase in the numbers of EVs. The higher the aggregated storage capacity, the more the system is able to smooth out peaks and fill in the valleys and maintain feeder demand within desired limits of operation even at increased penetration thereby eliminating the overload risk as well as postponing expensive upgrades to the network. Another strength of this study is that it focuses on the real world operating conditions. V2G was initially implemented in Kathmandu, Nepal at the 11 kV Baneshwor feeder using realistic load profiles, feeder characteristics and EV profiles. This makes the findings to be based on realities that are practical as opposed to idealized assumptions. The robustness was subsequently verified by implementing the strategy on the IEEE 33-bus benchmark network with consistent results being provided in both systems confirming the generality and flexibility of the suggested V2G technique. Overall, this study makes V2G technology a scalable, and economically viable way of dealing with the problem of transport electrification. V2G has the benefit of making EVs active grid resources instead of passive loads, thus facilitating both increased flexibility and resilience of the distribution system, and also assists the EV owners directly by saving them money. This two-fold benefit is particularly applicable to the developing countries like Nepal, in which fast urbanization and insufficient capacity to expand the infrastructure needs innovative planning solutions. To sum up, coordinated V2G integration has great transformational power of the future power system. V2G can help to make electricity networks more reliable, efficient, and even more affordable with the proper set of control measures, a favorable tariff framework, and a gradual process of infrastructural development. The results given here will form a good basis of future studies, pilot projects, and policies that will ensure that electric vehicles, renewables and smart grid technologies are integrated in a single sustainable energy system.

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APPENDIX

```
function baneshwor_v2g()

clc; clear; close all;

Ts_min = 5;                         % time step (minutes)
T      = 24*60 / Ts_min;             % steps per day
dt_h   = Ts_min/60;                  % hours per step

% Baneshwor nominal bus loads + daily shape derived from MW
data
[sys,  daily_shape]  =  baneshwor_data(T);      %  sys.NB,
sys.busP_kw

pf_target = 0.95;                              % assumed feeder
PF

% Build time-series base load (per bus and feeder total)
[PDT_kw,   ~]   =   build_timeseries_load(sys,   daily_shape,
pf_target);  % NB x T
P_base       = sum(PDT_kw,1);                  % 1 x T feeder
base load (kW)

t_hr = (0:T-1) * dt_h;

%% ------------ 2. EV parameters and cohort windows ------
---------------
ev.Pch_max_kW           = 7.2;      % per-EV max AC charge
power
ev.Pdis_max_kW          = 6.0;      % per-EV max discharge
power
ev.eta_ch             = 0.94;
ev.eta_dis            = 0.94;
ev.SOCmin           = 0.20;    % absolute min SoC (fraction
of capacity)
ev.reserve_frac       = 0.30;     % reserve SoC fraction for
V2G
ev.avg_need_kWh       = 18;       % mean daily energy need
ev.std_need_kWh       = 6;        % std dev of daily need
```

```
ev.batt_mean            = 52;       % mean battery capacity (kWh)
ev.batt_std           = 10;
ev.SOC0_mean          = 0.35;     % initial SoC mean
ev.SOC0_std           = 0.15;
ev.SOCgoal_mean       = 0.80;     % target SoC mean
ev.SOCgoal_std        = 0.10;
ev.participation_v2g   = 0.40;     % 40% of EVs willing to discharge

% 4 cohort arrival/availability windows (hours)
coh_win = [ ...
    6   9;     % Cohort 1: early morning home / top-up
    9   17;    % Cohort 2: workplace stay
    17  22;    % Cohort 3: evening home
    22  6];    % Cohort 4: overnight home (wraps midnight)
C = size(coh_win,1);

% EV penetration sweep (fraction of equivalent customers)
pen_list = 0.05:0.05:0.50;      % 5% to 50% in 5% steps
nPen     = numel(pen_list);

% Tariff (same for Baneshwor)
price = mk_tariff(T);           % 1 x T, currency/kWh

%% ------------ 3. KPI arrays ------------------------------------------

peak_un          = zeros(1,nPen);
peak_v2g         = zeros(1,nPen);
peak_red_abs     = zeros(1,nPen);
peak_red_pct     = zeros(1,nPen);

PAR_un           = zeros(1,nPen);
PAR_v2g          = zeros(1,nPen);
PAR_red_pct      = zeros(1,nPen);

LF_un            = zeros(1,nPen);
LF_v2g           = zeros(1,nPen);
LF_improve       = zeros(1,nPen);

Pmin_un          = zeros(1,nPen);
Pmin_v2g         = zeros(1,nPen);
valley_lift      = zeros(1,nPen);
```

```
FI_flatten        = zeros(1,nPen);

cost_tot_un       = zeros(1,nPen);
cost_tot_v2g      = zeros(1,nPen);
cost_perEV_un     = zeros(1,nPen);
cost_perEV_v2g    = zeros(1,nPen);
saving_perEV      = zeros(1,nPen);
saving_pct_perEV = zeros(1,nPen);

E_charge_perEV_un  = zeros(1,nPen);
E_charge_perEV_v2g = zeros(1,nPen);

%% ------------ 4. Penetration loop -----------------------
-------------
for kPen = 1:nPen
    ev.penetration = pen_list(kPen);

    % Build EV cohorts for this penetration
    EV   = build_ev_cohorts(sys, ev, C, coh_win, T, Ts_min);
    N_EV = sum(EV.N(:));    % total EVs in feeder

    %% --- Uncontrolled charging -------------------------
-------------
    [PEV_un_kw, ~] = simulate_uncontrolled(PDT_kw, EV, ev,
T, Ts_min);
    P_tot_un       = P_base + PEV_un_kw;

    % Threshold for V2G: average uncontrolled feeder load
    P_limit = mean(P_tot_un);

    %% --- V2G controlled charging -----------------------
-------------
    [PEV_v2g_kw, ~] = simulate_v2g_control( ...
        PDT_kw, EV, ev, T, Ts_min, P_limit, PEV_un_kw);
    P_tot_v2g = P_base + PEV_v2g_kw;

    %% ---------- KPIs: Peak, PAR, LF, valley, flattening -
------------
    Ppeak_un  = max(P_tot_un);
    Ppeak_v2g = max(P_tot_v2g);
    Pavg_un   = mean(P_tot_un);
    Pavg_v2g  = mean(P_tot_v2g);
```

```
    peak_un(kPen)       = Ppeak_un;
    peak_v2g(kPen)      = Ppeak_v2g;
    peak_red_abs(kPen) = Ppeak_un - Ppeak_v2g;
    peak_red_pct(kPen)       =       100*(Ppeak_un       -
Ppeak_v2g)/Ppeak_un;

    PAR_un(kPen)        = Ppeak_un / Pavg_un;
    PAR_v2g(kPen)       = Ppeak_v2g / Pavg_v2g;
    PAR_red_pct(kPen)          =     100*(PAR_un(kPen)     -
PAR_v2g(kPen))/PAR_un(kPen);

    LF_un(kPen)         = Pavg_un / Ppeak_un;
    LF_v2g(kPen)        = Pavg_v2g / Ppeak_v2g;
    LF_improve(kPen)    = LF_v2g(kPen) - LF_un(kPen);

    Pmin_un(kPen)       = min(P_tot_un);
    Pmin_v2g(kPen)      = min(P_tot_v2g);
    valley_lift(kPen)   = Pmin_v2g(kPen) - Pmin_un(kPen);

    sigma_un            = std(P_tot_un,1);
    sigma_v2g           = std(P_tot_v2g,1);
    FI_flatten(kPen)    = 1 - sigma_v2g/max(sigma_un,1e-9);

    %% ---------- KPIs: Owner costs ----------------------
-------------
    cost_un  = owner_cost(PEV_un_kw,  price, Ts_min, N_EV);
    cost_v2g = owner_cost(PEV_v2g_kw, price, Ts_min, N_EV);

    cost_tot_un(kPen)       = cost_un.total;
    cost_tot_v2g(kPen)      = cost_v2g.total;
    cost_perEV_un(kPen)     = cost_un.cost_per_EV;
    cost_perEV_v2g(kPen)    = cost_v2g.cost_per_EV;
    saving_perEV(kPen)            =   cost_un.cost_per_EV   -
cost_v2g.cost_per_EV;
    saving_pct_perEV(kPen)  =  100  *  saving_perEV(kPen)  /
max(cost_perEV_un(kPen),1e-9);

    E_charge_perEV_un(kPen)   = cost_un.E_charge_per_EV;
    E_charge_perEV_v2g(kPen) = cost_v2g.E_charge_per_EV;

    %% ---------- Print console summary ------------------
-------------
```

```
    fprintf('\n=== Baneshwor: Penetration = %.0f %%
===\n',100*ev.penetration);
    fprintf('Total EVs in feeder          : %d\n', N_EV);
    fprintf('Peak_un / Peak_v2g (kW)           : %.1f /
%.1f\n',Ppeak_un,Ppeak_v2g);
    fprintf('Peak reduction                  : %.1f kW (%.1f
%%)\n', ...
        peak_red_abs(kPen), peak_red_pct(kPen));
    fprintf('PAR_un / PAR_v2g              : %.3f / %.3f (%.1f
%% red.)\n', ...
        PAR_un(kPen), PAR_v2g(kPen), PAR_red_pct(kPen));
    fprintf('LF_un / LF_v2g                : %.3f / %.3f (?LF
= %.3f)\n', ...
        LF_un(kPen), LF_v2g(kPen), LF_improve(kPen));
    fprintf('Pmin_un / Pmin_v2g            : %.1f / %.1f (lift
= %.1f kW)\n', ...
        Pmin_un(kPen), Pmin_v2g(kPen), valley_lift(kPen));
    fprintf('Flattening index FI                 : %.3f\n',
FI_flatten(kPen));
    fprintf('Cost per EV (un / v2g)          : %.3f / %.3f
(saving = %.3f)\n', ...
        cost_un.cost_per_EV,       cost_v2g.cost_per_EV,
saving_perEV(kPen));
    fprintf('Saving per EV (%%)                : %.2f %%\n',
saving_pct_perEV(kPen));
    fprintf('Daily charge energy per EV  : %.2f vs %.2f kWh
(un / v2g)\n', ...
        cost_un.E_charge_per_EV,
cost_v2g.E_charge_per_EV);

    %% ---------- Plots for this penetration -------------
-------------
    % Feeder load profile
    figure('Name',sprintf('Baneshwor    Feeder    Load
(Pen=%.0f%%)',100*ev.penetration), ...
           'Color','w');
    plot(t_hr, P_base,'b-','LineWidth',1.5); hold on;
    plot(t_hr, P_tot_un,'r-','LineWidth',1.5);
    plot(t_hr,          P_tot_v2g,'Color',[1          0.7
0],'LineWidth',1.5);
    yline(P_limit,'k-','LineWidth',1);
    xlabel('Hour'); ylabel('kW');
```

```
    legend('Base  (Non-EV)','Total  w/  Uncontrolled','Total
w/ V2G','P_{limit}', ...
           'Location','best');
    title(sprintf('Baneshwor: Base vs Uncontrolled vs V2G
(Pen=%.0f%%)', ...
          100*ev.penetration));
    grid on;

    % Owner cost components
    figure('Name',sprintf('Owner      Cost      Components
(Pen=%.0f%%)',100*ev.penetration), ...
           'Color','w');
    labels   =   {'Charge   cost','-   Discharge   credit','+
Degradation','= Total'};
    A    =    [cost_un.charge_cost;                         -
cost_un.discharge_credit; ...
         cost_un.deg_cost;          cost_un.total];
    B    =    [cost_v2g.charge_cost;                        -
cost_v2g.discharge_credit; ...
         cost_v2g.deg_cost;         cost_v2g.total];
    bar([A B]);
    set(gca,'XTickLabel',labels,'XTickLabelRotation',20);
    legend('Uncontrolled','V2G
Controlled','Location','best');
    ylabel('currency/day');
    title(sprintf('Baneshwor   Owner   Cost   Components,
Pen=%.0f%%', ...
          100*ev.penetration));
    grid on;
end

%% ------------ 5. Summary plots vs penetration ----------
-------------
pen_pct = 100 * pen_list;

% Peak
figure('Name','Baneshwor Peak vs Penetration','Color','w');
plot(pen_pct, peak_un,'-o','LineWidth',1.5); hold on; grid
on;
plot(pen_pct, peak_v2g,'-s','LineWidth',1.5);
xlabel('EV  Penetration  (%)');  ylabel('Peak  feeder  load
(kW)');
```

```
legend('Uncontrolled','V2G Controlled','Location','best');
title('Baneshwor Peak Substation Power vs EV Penetration');

% PAR
figure('Name','Baneshwor PAR vs Penetration','Color','w');
plot(pen_pct, PAR_un,'-o','LineWidth',1.5); hold on; grid
on;
plot(pen_pct, PAR_v2g,'-s','LineWidth',1.5);
xlabel('EV Penetration (%)'); ylabel('Peak-to-Average
Ratio');
legend('Uncontrolled','V2G Controlled','Location','best');
title('Baneshwor PAR vs EV Penetration');

% Load Factor
figure('Name','Baneshwor Load Factor vs
Penetration','Color','w');
plot(pen_pct, LF_un,'-o','LineWidth',1.5); hold on; grid
on;
plot(pen_pct, LF_v2g,'-s','LineWidth',1.5);
xlabel('EV Penetration (%)'); ylabel('Load Factor');
legend('Uncontrolled','V2G Controlled','Location','best');
title('Baneshwor Load Factor vs EV Penetration');

% Flattening index
figure('Name','Baneshwor Flattening Index vs
Penetration','Color','w');
plot(pen_pct, FI_flatten,'-o','LineWidth',1.5); grid on;
xlabel('EV Penetration (%)'); ylabel('FI = 1 -
\sigma_{v2g}/\sigma_{un}');
title('Baneshwor Load Profile Flattening vs EV
Penetration');

% Cost per EV
figure('Name','Baneshwor Cost per EV vs
Penetration','Color','w');
plot(pen_pct, cost_perEV_un,'-o','LineWidth',1.5); hold on;
grid on;
plot(pen_pct, cost_perEV_v2g,'-s','LineWidth',1.5);
xlabel('EV Penetration (%)'); ylabel('Cost per EV
(currency/day)');
legend('Uncontrolled','V2G Controlled','Location','best');
title('Baneshwor Daily Cost per EV vs EV Penetration');
```

```
% Saving per EV (absolute)
figure('Name','Baneshwor Saving per EV vs
Penetration','Color','w');
plot(pen_pct, saving_perEV,'-o','LineWidth',1.5); grid on;
xlabel('EV Penetration (%)'); ylabel('Saving per EV
(currency/day)');
title('Baneshwor Net Daily Saving per EV (V2G vs
Uncontrolled)');

% Saving per EV (%)
figure('Name','Baneshwor Saving %% per EV vs
Penetration','Color','w');
plot(pen_pct, saving_pct_perEV,'-o','LineWidth',1.5); grid
on;
xlabel('EV Penetration (%)'); ylabel('Saving per EV (%)');
title('Baneshwor Percentage Daily Cost Saving per EV');

end % ===== end main =====


%% ================== Baneshwor data & load-shape
======================
function [sys, daily_shape] = baneshwor_data(T)
% Build Baneshwor nominal bus loads and daily shape from
measured MW.

% --- 1) Original nominal KW per bus ---
P0_kw = [ ...
    0;      % Bus 1 (slack)
    85;     % Bus 2
    85;     % Bus 3
    170;    % Bus 4
    170;    % Bus 5
    85;     % Bus 6
    170;    % Bus 7
    170;    % Bus 8
    170;    % Bus 9
    170;    % Bus 10
    85;     % Bus 11
    212.5;  % Bus 12
    170;    % Bus 13
    170;    % Bus 14
    85;     % Bus 15
```

```
    170;    % Bus 16
    85;     % Bus 17
    170;    % Bus 18
    85;     % Bus 19
    85;     % Bus 20
    170;    % Bus 21
    255;    % Bus 22
    170;    % Bus 23
    85;     % Bus 24
    85];    % Bus 25

NB = numel(P0_kw);

% --- 2) Measured feeder MW at specific times ( NEA table)
---
t_meas = [ ...
     0;  1;  2;  3;  4;  5; ...
     6;  6.5; 7;  7.5; 8;  9; 10; 11; 12; 13; 14; 15; 16;
17; ...
    17.5; 18; 18.5; 19; 19.5; 20; 21; 22; 23; 24];   % hours

P_MW = [ ...
    1.2; 1.0; 0.9; 0.9; 0.9; 1.0; ...
    1.2; 1.4; 1.6; 1.9; 1.8; 1.9; 2.0; 2.0; 1.9; 2.0; 1.9;
1.9; 1.9; 1.8; ...
    2.0; 2.5; 2.6; 2.6; 2.5; 2.4; 2.1; 1.7; 1.4; 1.2];   %
MW

% --- 3) Interpolate to 15-min resolution and normalize to
mean = 1 ---
dt_h = 24 / T;                          % should be 0.25 for
Ts=15 min
t_grid = (0:T-1)' * dt_h;              % 0..24-?
P_MW_grid = interp1(t_meas, P_MW, t_grid, 'pchip');

% Normalized daily shape
daily_shape_raw = P_MW_grid(:);        % MW
daily_shape     = daily_shape_raw / mean(daily_shape_raw);

% --- 4) Scale nominal bus loads to match average MW level
---
Pavg_MW  = mean(daily_shape_raw);           % MW
Pavg_kW  = Pavg_MW * 1000;                  % kW
```

```
scale    = Pavg_kW / sum(P0_kw);           % scaling factor
P_bus_kw = scale * P0_kw;                  % scaled nominal
bus loads

sys.NB       = NB;
sys.busP_kw  = P_bus_kw(:);                 % NB x 1

end


%%     =================     Generic    helper    functions
==========================
function    [P_kw,   Q_kvar]   =   build_timeseries_load(sys,
daily_shape, pf_target)
% Build time-series base load for each bus using normalized
daily shape.

NB    = sys.NB;
P_nom = sys.busP_kw(:);              % NB x 1 nominal kW

P_kw  = P_nom * daily_shape(:)';     % NB x T

phi         = acos(pf_target);
Q_P_ratio   = tan(phi);
Q_kvar      = P_kw * Q_P_ratio;      % NB x T
end


function price = mk_tariff(T)
% Simple 3-period TOU tariff (currency/kWh) for Baneshwor.

t = linspace(0,24,T);
price = 8 * ones(1,T);           % base rate

price(t>=6  & t<10) = 10;        % morning shoulder
price(t>=10 & t<17) = 9;         % mid-day
price(t>=17 & t<22) = 12;        % evening peak
price(t>=22 | t<6)  = 7;         % valley / night

end
```

```
function EV = build_ev_cohorts(sys, ev, C, coh_win, T,
Ts_min)
% Aggregate EV cohorts per bus + availability masks (4
cohorts incl. night)

rng(7);                    % reproducible
NB   = sys.NB;
dt_h = Ts_min/60;
h    = (0:T-1)*dt_h;       % hour grid

C = size(coh_win,1);       % ensure consistency

% 1) distribute EVs across buses proportional to active
power
PD      = max(sys.busP_kw(:),0);
totalP  = max(sum(PD),1e-9);
w       = PD / totalP;

cust_per_kw = 1/1.5;                            % approx
customers per kW
Ncust       = max(1, round(totalP * cust_per_kw));
Nev_total   = max(1, round(ev.penetration * Ncust));

try
    Nev_bus = mnrnd(Nev_total, w(:)')';       % NB x 1
catch
    Nev_bus = round(w * Nev_total);
    d       = Nev_total - sum(Nev_bus);
    if d>0
        [~,ix] = sort(w,'descend');
        Nev_bus(ix(1:d)) = Nev_bus(ix(1:d)) + 1;
    elseif d<0
        [~,ix] = sort(w,'ascend');
        Nev_bus(ix(1:-d)) = max(0, Nev_bus(ix(1:-d))-1);
    end
end

% 2) preallocate struct
EV.NB          = NB;
EV.C           = C;
EV.eta_ch      = ev.eta_ch;
EV.eta_dis     = ev.eta_dis;
EV.SOCmin      = ev.SOCmin;
```

```
EV.reserve_frac = ev.reserve_frac;

EV.N             = zeros(NB,C);
EV.Ecap_kWh      = zeros(NB,C);
EV.SOC0_kWh      = zeros(NB,C);
EV.Egoal_kWh     = zeros(NB,C);
EV.Pch_max_busC  = zeros(NB,C);
EV.Pdis_max_busC = zeros(NB,C);
EV.dis_ok        = false(NB,C);
EV.avail         = false(NB,C,T);

% 3) Build cohorts for each bus
for b = 1:NB
    n = Nev_bus(b);
    if n==0, continue; end

    baseq              = floor(n/C);
    counts             = baseq * ones(1,C);
    counts(1:mod(n,C)) = counts(1:mod(n,C)) + 1;

    pV2G  = ev.participation_v2g;
    N_v2g = round(counts * pV2G);

    for c = 1:C
        Nco = counts(c);
        EV.N(b,c) = Nco;
        if Nco==0, continue; end

        % battery statistics
        cap = max(20, ev.batt_mean +
ev.batt_std*randn(Nco,1));
        soc0 = min(max(ev.SOC0_mean +
ev.SOC0_std*randn(Nco,1), 0.05), 0.95);
        socg = min(max(ev.SOCgoal_mean +
ev.SOCgoal_std*randn(Nco,1), 0.10), 0.98);
        need = max(3, ev.avg_need_kWh +
ev.std_need_kWh*randn(Nco,1));

        EV.Ecap_kWh(b,c)  = sum(cap);
        EV.SOC0_kWh(b,c)  = sum(cap .* soc0);
        EV.Egoal_kWh(b,c) = max(sum(cap .* socg),
EV.SOC0_kWh(b,c)+sum(need));
```

```
        EV.Pch_max_busC(b,c)  = Nco      * ev.Pch_max_kW;
        EV.Pdis_max_busC(b,c) = N_v2g(c) * ev.Pdis_max_kW;
        EV.dis_ok(b,c)        = (N_v2g(c) > 0);

        win = coh_win(c,:);
        if win(2) > win(1)
            m = (h>=win(1) & h<win(2));
        else
            m = (h>=win(1) | h<win(2));    % overnight
        end

        noise = (rand(1,T) > 0.04);      % 96% availability
within window
        m     = m & noise;

        EV.avail(b,c,:) = reshape(m,1,1,T);
    end
end
end


function [PEV_kw, E_kWh] = simulate_uncontrolled(PDT_kw,
EV, ev, T, Ts_min)
% Uncontrolled charging: charge as soon as available until
Egoal is reached.

dt_h = Ts_min/60;
NB   = EV.NB;
C    = EV.C;

E_kWh  = EV.SOC0_kWh;           % NB x C
PEV_kw = zeros(1,T);

for t = 1:T
    P_step = 0;
    for b = 1:NB
        for c = 1:C
            if ~EV.avail(b,c,t), continue; end

            E     = E_kWh(b,c);
            Egoal = EV.Egoal_kWh(b,c);
            if E >= Egoal, continue; end
```

```
            Pmax     = EV.Pch_max_busC(b,c);
            E_needed = max(Egoal - E, 0);
            P_need   = E_needed/(dt_h*EV.eta_ch);
            P        = min(Pmax, P_need);

            P_step         = P_step + P;
            E_kWh(b,c)     = E + P*dt_h*EV.eta_ch;
        end
    end
    PEV_kw(t) = P_step;
end
end


function [PEV_kw, E_kWh] = simulate_v2g_control( ...
    PDT_kw, EV, ev, T, Ts_min, P_limit, PEV_un_kw)
%  Threshold-based  V2G  control  with  approximate  feeder-
energy neutrality.

dt_h = Ts_min/60;
NB   = EV.NB;
C    = EV.C;

E_kWh  = EV.SOC0_kWh;      % NB x C
PEV_kw = zeros(1,T);

P_base = sum(PDT_kw,1);    % 1 x T

for t = 1:T
    P_step = 0;
    P0     = P_base(t);

    % mode decision based on base load relative to P_limit
    if P0 >= P_limit
        mode = 1;   % discharge
    else
        mode = 0;   % charge
    end

    Pcap = [];
    idx  = [];

    for b = 1:NB
```

```
        for c = 1:C
            if ~EV.avail(b,c,t), continue; end

            E     = E_kWh(b,c);
            Egoal = EV.Egoal_kWh(b,c);

            m_rem = squeeze(EV.avail(b,c,t:T));
            Nrem  = sum(m_rem);
            if Nrem <= 0, continue; end

            if ~mode   % charging
                if E >= Egoal, continue; end
                E_need = max(Egoal - E, 0);
                P_req  = E_need/(Nrem*dt_h*EV.eta_ch);
                Pmax          =   min(EV.Pch_max_busC(b,c),
P_req*1.5);
                if Pmax <= 0, continue; end
                Pcap(end+1,1) = Pmax;
                idx(end+1,:)  = [b c 0];
            else       % discharging
                if ~EV.dis_ok(b,c), continue; end
                Ecap  = EV.Ecap_kWh(b,c);
                E_res = EV.reserve_frac * Ecap;
                if E <= E_res, continue; end
                Pmax_dis = EV.Pdis_max_busC(b,c);
                E_margin = E - E_res;
                PmaxE    = E_margin/(dt_h*EV.eta_dis);
                Pmax     = min(Pmax_dis, PmaxE);
                if Pmax <= 0, continue; end
                Pcap(end+1,1) = Pmax;
                idx(end+1,:)  = [b c 1];
            end
        end
    end

    if isempty(Pcap)
        PEV_kw(t) = 0;
        continue;
    end

    P_target = P_limit - P0;

    if ~mode  % charging
```

```
        P_target    = max(P_target,0);
        P_total_cap = sum(Pcap);
        P_alloc     = min(P_target,P_total_cap);
        frac        = Pcap / max(P_total_cap,1e-9);
        P_vec       = frac * P_alloc;
    else      % discharging
        P_target    = min(P_target,0);
        P_total_cap = sum(Pcap);
        P_alloc        =  max(P_target,-P_total_cap);      %
negative
        frac        = Pcap / max(P_total_cap,1e-9);
        P_vec         = frac *  (-P_alloc);                 %
positive magnitudes
    end

    % apply per-cohort power
    for k = 1:numel(P_vec)
        b = idx(k,1); c = idx(k,2); flag = idx(k,3);
        P = P_vec(k);

        if flag == 0   % charge
            P_step       = P_step + P;
            E_kWh(b,c)   = E_kWh(b,c) + P*dt_h*EV.eta_ch;
        else           % discharge
            P_step       = P_step - P;
            E_kWh(b,c)   = E_kWh(b,c) - P*dt_h/EV.eta_dis;
        end
    end

    PEV_kw(t)  = P_step;
end

% ---- Feeder-energy neutrality wrt uncontrolled EV charging
----------
E_un   = sum(PEV_un_kw)*dt_h;
E_v2g = sum(PEV_kw)*dt_h;
if abs(E_v2g - E_un) > 0.01*max(abs(E_un),1e-9)
    scale   = E_un / max(E_v2g,1e-9);
    PEV_kw = PEV_kw * scale;
end

end
```

```
function cost = owner_cost(PEV_kw, price, Ts_min, N_EV)
% Owner cost components and per-EV daily metrics.

dt_h   = Ts_min/60;
E_step = PEV_kw * dt_h;           % kWh (positive=charging,
negative=discharge)

E_charge    = sum(max(E_step,0));
E_discharge = sum(max(-E_step,0));

charge_cost      = sum(max(E_step,0) .* price);
discharge_credit = sum(max(-E_step,0) .* price * 0.9);   %
90% energy credit

lambda_deg = 0.03;                      % degradation cost per
kWh throughput
E_through  = E_charge + E_discharge;
deg_cost   = lambda_deg * E_through;

total_cost = charge_cost - discharge_credit + deg_cost;

N = max(N_EV,1);
cost_per_EV        = total_cost / N;
E_charge_per_EV    = E_charge / N;
E_discharge_per_EV = E_discharge / N;
E_through_per_EV   = E_through / N;

cost.charge_cost        = charge_cost;
cost.discharge_credit   = discharge_credit;
cost.deg_cost           = deg_cost;
cost.total              = total_cost;

cost.cost_per_EV        = cost_per_EV;
cost.E_charge           = E_charge;
cost.E_discharge        = E_discharge;
cost.E_through          = E_through;
cost.E_charge_per_EV    = E_charge_per_EV;
cost.E_discharge_per_EV = E_discharge_per_EV;
cost.E_through_per_EV   = E_through_per_EV;
end
```