GRID INTEGRATION LABORATORY
IIT BOMBAY

In cooperation with
Government of India
Ministry of Power
Central Electricity Authority

# IMPLEMENTATION OF VEHICLE-TO-EVERYTHING (V2X) IN INDIA

## Report 1

## FUNDAMENTALS OF VEHICLE-TO-EVERYTHING(V2X) : TECHNOLOGY, ENABLERS AND CHALLENGES

A study conducted by
Indian Institute of Technology (IIT) Bombay
In cooperation with CEA, Ministry of Power

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Insightful and constructive inputs provided by various stakeholders consulted during this study is also highly appreciated.

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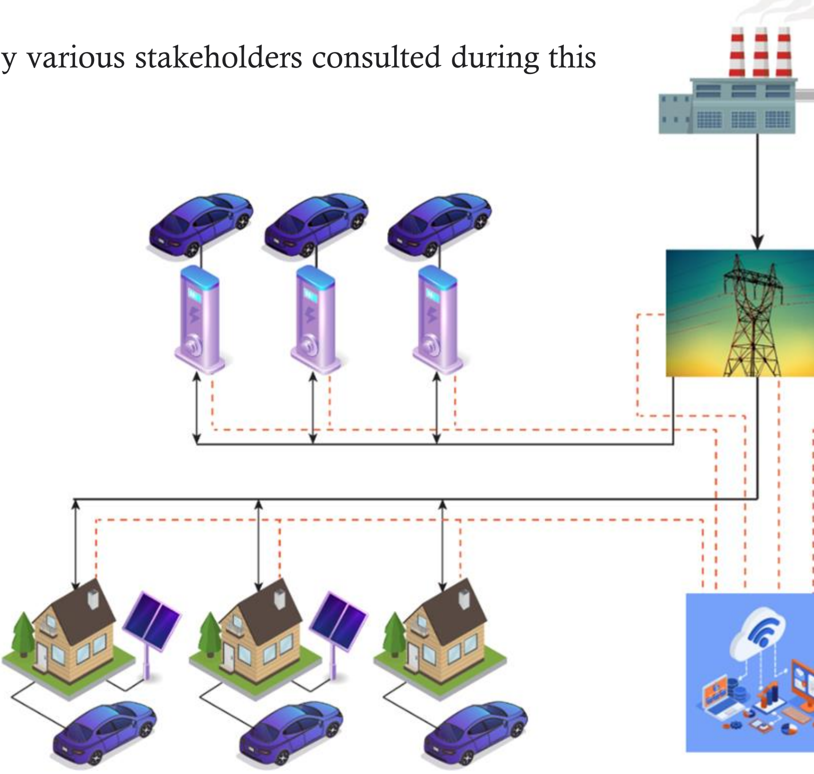

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# FOREWORD

India has committed to be net-zero by 2070. All sectors including transport sector need to take action to achieve this. Electrification of the transport sector which is one of the major source of carbon emission, will play a critical role in decarbonizing the transportation energy vertical and in achieving net-zero target of the country. With the ambitious targets of Electric Vehicle (EV) adoption, India has initiated several measures to electrify the transport sector through different initiatives, such as, the National Electric Mobility Mission Plan (NEMMP) 2020, Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, and Electric Vehicle (EV) policies at State/UT level.

Adequate charging infrastructure and its grid integration plays a critical role in seamless adoption of electric vehicles. While EV integration can introduce several challenges in the grid, particularly at distribution system level, such as impact on voltage, increased losses, congestion, power quality and unbalancing issues, the EV charging technology can be potentially managed to not only minimize the grid impacts, but also exploited to support the the grid in several ways. With the increased penetration of EVs, for example, battery storage in BEVs, which remains largely underutilized across the vehicle segments (2/3/4 wheeler and heavy duty vehicles including E-buses), can be utilized for various grid management/support services. Vehicle-to-grid (V2G) that allows reverse power flow from battery of EV to the grid and vice versa, has enormous potential to open up a range of potential grid support services, such as, increased uptake of renewable energy (RE) generation, improve grid management, and efficient grid operation. However, since V2G technology is relatively new, it is important to understand how in the Indian context, V2G can be put to the best use to the advantage of electricity grid and the overall Indian EV ecosystem.

I am pleased to note that realizing the pressing need to analyze and understand how EVs through bidirectional power flow can be implemented in India, IIT Bombay has undertaken a timely study on “Implementation of Vehicle-to-Everything (V2X) in India” which is a first of its kind study in India. Through this study, Grid Integration Lab at IIT Bombay has developed two reports focussing on a detailed technical review, market survey of V2X technology and its relevance in Indian EV ecosystem, and techno economic analysis backed recommendations for V2X adaption in Indian context. The study has comprehensively analyzed various V2X technologies (V2G, V2H, V2B, V2L etc.) and its applications in Indian context, identified key gaps in adoption of V2X technology in India, and offered a way forward for adoption of V2X in India through various recommendations backed by detailed techno-economic analysis. I am sure this study through its quality reports on this important topic of V2G and other V2X applications will be beneficial to different stakeholders with useful inputs for various V2X applications including regulatory aspects for V2G adoption in India. This study is expected to serve as a constructive reference/input for grid integration of V2G technology and its grid connectivity standards for Indian grid.

I congratulate IIT Bombay for conducting this timely study on an important topic of implementation of V2G in India and publishing its findings through two technical reports. I also appreciate the effort of Shri Ashok Kumar Rajput, Member, Central Electricity Authority and his team’s association in preparation of this report.

**(Ghanshyam Prasad)**

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Prof. Willett Kempton,
Professor at the University of Delaware in the College of Earth, Ocean and Environment, and in the Department of Electrical and Computer Engineering.

# FOREWORD

Decarbonizing transportation is an essential part of addressing the challenge of climate change. India, consistently with its carbon emission reduction targets, is achieving electrification of the transportation sector toward the targets for EV adoption set both at the National and State level. However, adequate charging infrastructure and the integration of charging with the electric grid will be crucial to achieve the transition to sustainable mobility. Although EV charging load introduces challenges in the grid, the smart use of EV charging infrastructure can unlock a new potential of the mobility sector to benefit grid management. Vehicle-to-grid (V2G) has a great potential to help in efficient and optimal grid management, particularly, in India which has one of the largest power grids, and is also one of the largest vehicle producing countries. Since India is at an early stage of EV adoption, it is well positioned to plan adoption of V2G in the country through the contemporary understanding of technical, regulatory and policy interventions.

I am pleased to note that the Grid Integration Lab of IIT Bombay has undertaken this important and timely study of “Implementation of Vehicle-to-Everything (V2X) in India”, and I believe that the two reports of this study will serve as a reference document for V2X implementation in India. I hope that the findings of this study will inform Government and Industry stakeholders in India, and create momentum for policies facilitating adoption of V2G and other V2X applications in the Indian EV ecosystem. India has so much talent, a large market, and low-cost IT and manufacturing infrastructure, all of which can drive V2X forward.

At University of Delaware, I got the original idea of using electric vehicles to support the electric grid, published in 1997, and colleagues and I have been developing it ever since. Little did we know that our idea 26 years later would develop into the concept of Vehicle-to-Everything (V2X) and find its way to India, one of the largest car markets in the world.

I congratulate the IIT Bombay team for this interesting study. I am looking forward to following the progress of V2X in India and I wish all the best luck in making V2X a success in India and beyond.

Willett Kempton

Prof. Willett Kempton

सत्यमेव जयते

केन्द्रीय विद्युत विनियामक आयोग
**CENTRAL ELECTRICITY REGULATORY COMMISSION**

के वि वि आयोग
CERC

*Indu Shekhar Jha*
*Member*

## Foreword

Climate change driven global temperature rise is having far reaching consequences, particularly on the modern human civilisation. India has embarked on the path of renewable energy (RE) based sustainable transition of power sector towards clean energy-based system with ambitious targets set for RE integration by 2030. In COP26 held in Glasgow, India committed to reaching net-zero carbon emission target by the year 2070. However, in order to achieve carbon neutral target, besides power sector, it is critical to address carbon emissions from other energy sectors as well. Transportation sector contributes approximately 23% of total carbon emissions, thereby highlighting the pressing need to decarbonise the transportation sector. In order to address carbon emission from the transportation sector, India has already started electrifying its transportation sector across all the vehicle segments for which sector coupling between power and transportation sectors is crucial. Forum of Regulators, in its report on 'Energy Storage and Electric Vehicles' (Nov 2022) have examined the regulatory challenges and recommended enabling policy and regulatory framework for effective and smooth integration of EVs with the Indian grid.

E-mobility of the transportation sector introduces new demand with unique characteristics to the power system through Electric Vehicle (EV) charging load. EV charging load can result in various challenges in the grid operation, but also has a significant potential to help in grid management and increased update of RE integration. Therefore, to address challenges of EV integration and unlock opportunities from EVs & charging infrastructure, it is important to have a deeper understanding of EV integration enabled through constructive studies.

I am pleased to note that Grid Integration Lab IIT Bombay has undertaken an important and first of its kind study in India "*Implementation of Vehicle-to-Everything (V2X) in India*" that analyses implementation of emerging EV integration technologies including Vehicle-to-Grid (V2G) technology in the Indian grid. This study provides technical, regulatory and policy recommendations for seamless adoption of V2X in India derived from primary research including techno-economic analysis of V2X implementation, secondary research and stakeholder consultations. Since India is at early stage of EV adoption, the outcome this study documented in two reports is expected to help the relevant stakeholders including OEMs, policy and regulatory decision makers in taking timely and effective measures for implementation of V2X in Indian EV ecosystem.

I congratulate IIT Bombay team for taking up this timely study on V2X implementation in India and documenting its outcome in two important reports for the benefit of all the stakeholders of EV ecosystem. I am sure the outcome of this study will benefit different stakeholders including DISCOMS, Grid operators, regulatory bodies, relevant OEMS, research community and think tanks.

**(Indu Shekhar Jha)**

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# Foreword

The consequences of climate change are far-reaching, impacting not only the environment but also posing significant risks to human health, food security, water resources, and biodiversity. Urgent and coordinated efforts are imperative to mitigate greenhouse gas emissions, adapt to the changes already underway, and foster international collaboration to build a resilient and sustainable future. To tackle the climate issue, in the recently concluded COP26 in Glasgow, India committed to reaching net-zero target by the year 2070. To curtail carbon emissions, in addition to ambitious renewable energy integration targets, India has set ambitious targets for reducing emissions in the transportation sector.

The global transportation landscape is evolving, with electric mobility emerging as a key player in redefining how we envision transportation, energy, and environmental stewardship. Access to electricity and mobility are two of the most significant markers for defining modern life. Vehicle to Everything (V2X) is the epitome of the coupling of this transportation and the other energy carriers. With V2X enabling the use of the energy storage unit of the EV for different applications, EVs can be used as flexibility resource for better grid management. The study "Implementation *of Vehicle-to-Everything (V2X) in India*" undertaken by Grid Integration Lab IIT Bombay is an important and timely study for advanced development of Indian EV ecosystem, particularly in the space of Vehicle-to-Grid (V2G) adoption in India. This first of its kind study in India delves into the intricate web of factors shaping the V2X landscape, from requirements in hardware to the need for capable charging infrastructure supporting V2X, and policy & regulatory interventions required for seamless adoption of the technology in India. It explores the economic implications, policy frameworks, and the dynamic interplay between manufacturers, EV users, and decision-making agencies, all contributing to the V2X ecosystem.

Importantly, the study provides information on different applications of V2X such as Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), Vehicle-to-Vehicle (V2V) and Vehicle-to-Load (V2L), their enablers, requirements and potential benefits. The study also provides a much-needed techno-economic analysis of different V2X applications in an Indian context, that can help Indian stakeholders in estimating the potential of V2X.

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I extend my congratulations to the IIT Bombay team for conducting this much needed study of V2X and preparing the two important reports for the benefit of different stakeholders of EV ecosystem. Their collective efforts have produced a valuable resource that not only elucidates the current state of electric vehicles but also paves the way for informed decisions and strategic planning in our pursuit of a sustainable and greener future. I am sure these study reports will serve as a catalyst for ongoing discourse, innovation, and cooperation as we collectively strive to usher in an era where electric vehicles play a central role in driving us towards a more sustainable and harmonious coexistence with our planet.

(Alok Tandon)

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# Chapter 1. Introduction

Climate change is regarded as the "greatest peril contemporary humanity has ever faced," with far-reaching consequences across numerous sectors. India is already witnessing the plights of climate change, with pollution killing almost 2.3 million in 2019 alone[1] and a 55% increase in deaths due to extreme heat between 2000-2004 and 2017-2021[2]. India is the world's 4th largest emitter of CO2 and the transportation sector is the third largest emitter in the country. To tackle the climate crisis, globally the transportation sector is gradually transitioning from fossil fuel powered Internal Combustion Engine based vehicles to electric vehicles (EVs). In addition to reduced emissions, the demand for EVs is being driven by national efforts/targets aimed at reducing reliance on oil imports.

**Climate change is not the future. India is in a climate emergency**

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[1] BBC, "Lancet study: Pollution killed 2.3 million Indians in 2019", May, 2022. https://www.bbc.com/news/world-asia-india-61489488

[2] BBC, "India heatwave: High temperatures killing more Indians now, Lancet study finds", October, 2022. https://www.bbc.com/news/world-asia-india-63384167

On November 2021, at the COP26 event in Glasgow, India committed to becoming net-zero by 2070. In accordance with this commitment different policies, both at the central and state level have been introduced for the promotion of EVs. As of Feb 2023, 25 states and Union territories have each released individual state EV policies. These policies include different financial support for the purchase of EVs, EV charging infrastructure and also provide different tax benefits and privileges. These policies have resulted in a gradual increase in EV sales as can be seen in Figure 1:1. As of January 2023, a total of 20 lakh EVs are on Indian roads. Of these, there are roughly 83 thousand electric cars (e4W), 9.9 lakhs electric three wheelers (e3W) and 9.75 lakhs electric two wheelers (e2W). However, looking at the overall transportation landscape in the country only 0.4% of the total 2W stock, 11% of the total 3W stock and 0.12% of the 4W stock have been electrified as shown in Figure 1:2. So, there is still a massive opportunity for growth. While there is a mention of Vehicle-to-Everything (V2X) in some of the State EV policies, the bidirectional EV charging and its adoption has been largely missing so far in the EV polices/schemes.

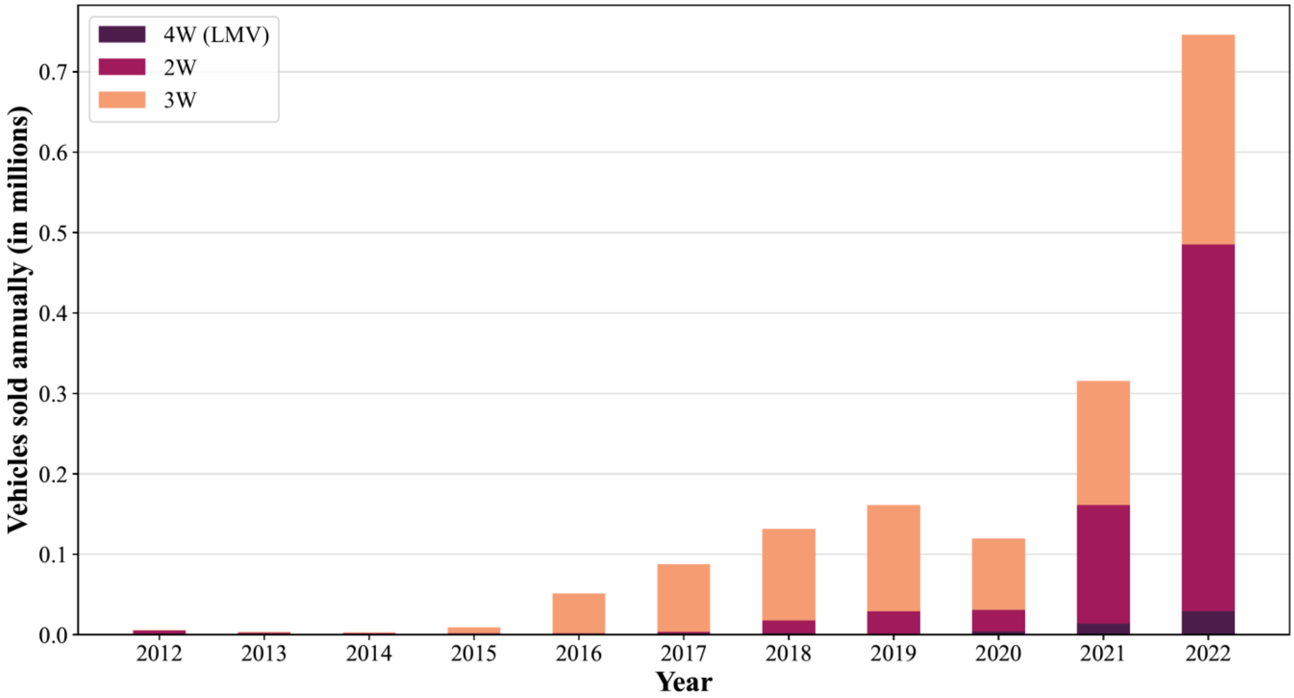

*Figure 1:1: Growth of annual EV sales in India (Source: Vahansewa)*

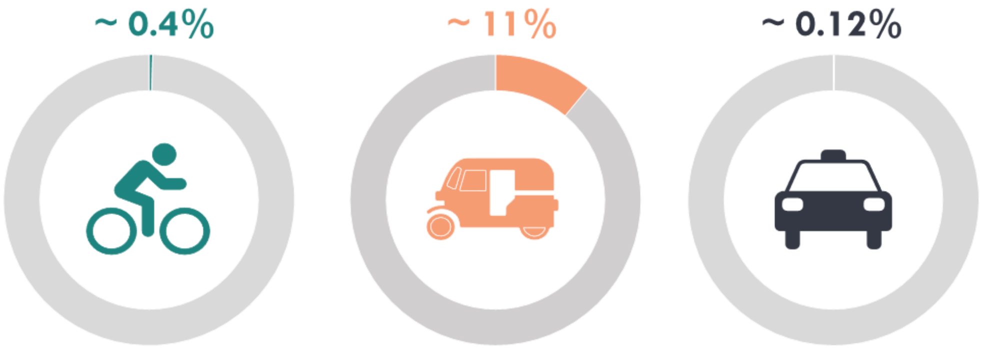

*Figure 1:2: Percentage of stock electrified in India as of January 2023 (Source: Vahansewa)*

Charging EV batteries introduces additional stress on the electricity distribution grid. As the proportion of EVs in the distribution system rises, the impact of EV charging on distribution system may become significant. While EV integration can introduce several technical challenges, such as impact on voltage, increased losses, congestion, power quality and unbalancing issues, the EV charging technology can be potentially managed to not only minimize the grid impacts, but also exploited to help the distribution system management in several ways. V1G (managed charging), which can control the charging rate of vehicles to ease stress on the grid, and V2X, which is the bidirectional flow of electricity from/to the vehicle, are the two approaches for managing EV charging load. V2G has a significant potential to support distribution and transmission system through various services. Such methods can help utilities address the issue of network reliability in the event of high EV uptake. EV batteries which technically have bidirectional power flow can be used for different applications.

Bidirectional EV charging has enormous potential since these capabilities would open up a range of potential grid support services, such as, support increased uptake of renewable energy (RE) generation, improve grid management, and promote more efficient grid operation. Bidirectional charging allows EV mobile storage units to be utilised as a vital grid and energy management resources. Considering the ambitious targets of EV adoption in India and net zero target of the country, there is a need to understand the V2X technology, its integration with the grid, and optimal use of V2G for sustainable and seamless transition to electrified transportation sector. In this backdrop, this study is focused on V2X technology and its adoption in Indian EV ecosystem with primary focus on seamless integration of V2X technology with the electricity grid in Indian context, while considering both technical and economic feasibility.

## 1.1 Aim of the study

The aim of this study is to conduct a detailed study with high impact/ quality output that can supplement decision making by the Government of India including State Governments, distribution system operators, transmission system operators, planning and regulatory agencies and other stakeholders (EV industry etc.) to frame, adapt, and/or revise policies, regulations, technical charging standards, communication protocols related bidirectional EV charging, tariffs, interconnection regulations, etc.

## 1.2 Objectives of the Study

This study is primarily focused on a detailed technical review and market survey of V2X technology, and techno economic analysis backed recommendations for V2X adaption in Indian context. The review of V2X technology includes a detailed review of bidirectional charging enabled chargers and EVs. The system architecture which involves the interaction between different stakeholders of V2X, the communication infrastructure, and the roles and responsibilities of different stakeholders for implementation of different V2X use cases has been also critically analyzed in this study. These use cases include the utilization of V2X for peak load management, increased renewable energy (RE) integration, voltage and frequency support, vehicle to home (V2H), vehicle to building (V2B), vehicle to load (V2L), etc.

A detailed analysis, for gaining an understanding of the technical know-how of V2X has also been performed in this study, followed by techno-economic analysis to determine viability of V2X implementation in the Indian context. This study is expected to play a key role in determining techno-economic gaps including the policy and regulatory issues that need to be addressed for smooth V2X roll-out in India. The study finally provides recommendations to promote the growth of V2X in the Indian EV ecosystem.

## 1.3 Organization of the study reports

The main outcome of the study is documented in two technical reports. Each of the reports cover different aspects of V2X in a structured manner for effective, organized and easy dissemination of the study outcome.

- **Report 1:** Fundamentals of Vehicle-to-Everything (V2X): Technology, Enablers and Challenges
- **Report 2:** Techno-economic analysis and Way Forward for V2X implementation in India

# Chapter 2. Introduction to Vehicle-to-Everything (V2X)

Two of the most significant markers for defining modern life are easy access to electricity and mobility. This is often reflected on the number of resources including manpower that have been utilized by each country for their provision. In India the power sector and the transportation sector use enough fossil fuel to cumulatively contribute for more than half of the country's total $CO_2$ emissions. While historically transportation and electricity were distinct mutually independent sectors, the emergence of electric vehicles has led to increased coupling between the two. This sector coupling is epitomized by Vehicle-to-grid (V2G) as electricity, remunerations, and responsibilities flow in both directions between the EV and the grid[3]. This sector coupling can also profoundly impact and reshape the conceptions of the people on the utility of a vehicle.

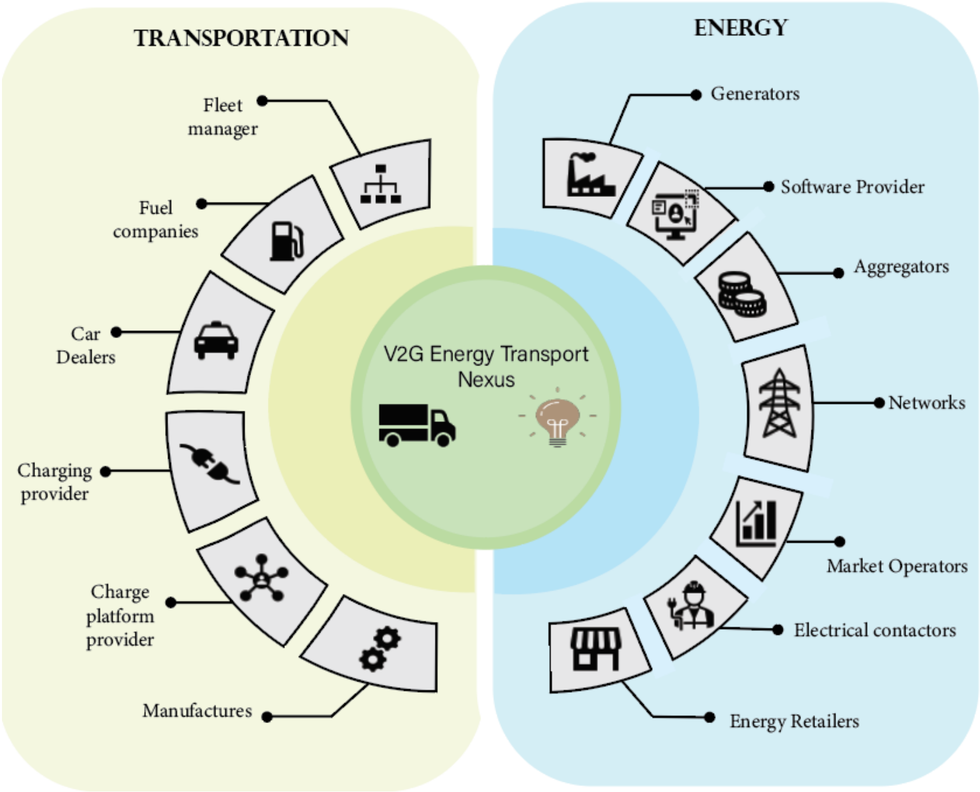

*Figure 2:1: V2G as the epitome of sector coupling between transportation and the energy sector*

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[3] Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, "The A to Z of V2G: A comprehensive analysis of vehicle-to-grid technology worldwide", Jan 2021

## 2.1 The Concept of V2X

Vehicle-to-Everything (V2X) is the use of EV batteries, sitting idle and not being currently used for mobility purposes, to provide valuable power back to ‘everything’. Here ‘everything’ or ‘X’ can be the electricity grid, a home, a building, independent loads or even other EVs as shown in Figure 2:2. Depending on to whom the EV is giving the power to, different terms have been coined as under,

- **Vehicle-to-Grid (V2G)** if the EV is feeding power back to the electrical grid
- **Vehicle-to-Home (V2H)** if the EV is feeding power to the home
- **Vehicle-to-Building (V2B)** if the EV is feeding power to a building
- **Vehicle-to-Load (V2L)** if the EV is feeding power to an individual load
- **Vehicle-to-Vehicle (V2V)** if the EV is feeding power to a different vehicle. This flexibility provided by EVs can prove to be a significant value addition for the grid operators.

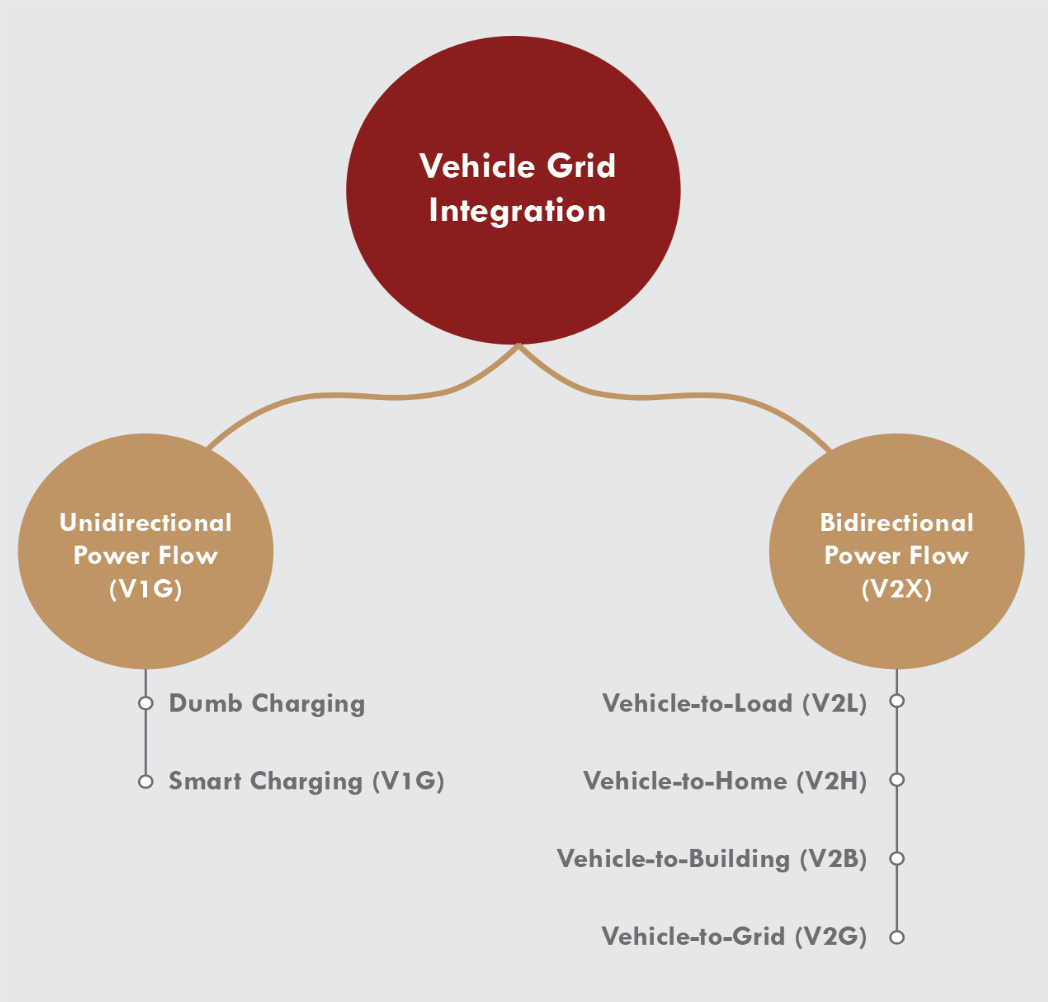

*Figure 2:2: Classification of Vehicle grid integration*

### 2.1.1 Vehicle-to-Grid

Electrical vehicle grid integration (VGI) services are in essence about managing the EV charging such that the impact on the electrical grid is reduced. V2G is an extension of the VGI concept in that, here in addition to just managing the charging, the energy in the EV battery is supplied back to the grid as and when needed. Here, based on the requirement of the grid the EV helps the grid operator in optimally managing the grid while also earning revenue for the service provided based on service contract between the utility and the customer.

Vehicle-to-Grid (V2G): A system where electric vehicles when connected to the grid through the EVSE, provide bidirectional flow of energy to the grid as and when required.

While the concept of V2G goes way back to 1997, it is yet to be fully commercialized. This is because of the extensive infrastructure that needs to be in place to facilitate V2G such as,

- V2G capable hardware (EV and the EV charger)
- A robust communication infrastructure
- Adequate regulations
- Accurate metering

An in-depth analysis of the gaps and challenges for adoption of V2X have been presented in Report 2 : Techno-economic analysis and recommendations for V2X implementation in India

In addition to the hardware, different entities and stakeholders needs close cooperation to facilitate V2G. The system architecture for V2G have been shown in Figure 2:3

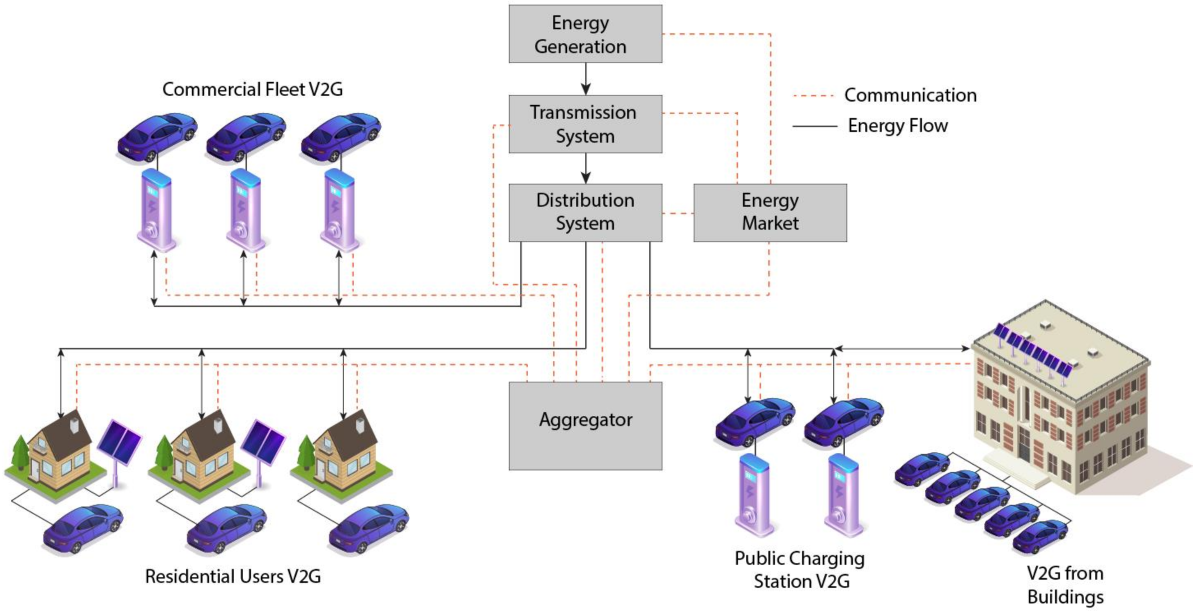

*Figure 2:3: V2G system architecture*

### 2.1.2 Vehicle-to-Home

Vehicle-to-home (V2H) allows the EV user to utilize the stored energy in the EV to be used as a power source for the home. Her, the energy in battery storage unit of the electric vehicle is used to provide power to the home in case of emergency, or for behind-the-meter optimization purposes. It is similar to having a portable energy storage device that can be used for different services by the EV user.

Customers may also store home-generated renewable energy in their car battery or replenish their battery from grid power when energy prices are cheap under the V2H system. Consumers can then draw energy from the system when needed or when retail tariffs are high. Customers may use this to reduce energy bills, encourage the use of renewable energy, and balance grid demand.

*Figure 2:4: V2H system*[4]

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[4] Gaton, Bryce, “We’re building a new house. What do we need for bidirectional EV charging?”, The Driven, May 13, 2019. https://thedriven.io/2019/05/13/were-building-a-new-house-what-do-we-need-for-bidirectional-ev-charging/

### 2.1.3 Vehicle-to-Building

Similar to V2H, in vehicle-to-building (V2B), instead of a single EV supplying a house, a fleet of EVs are supplying a larger building such as an office, malls etc. Here, too the fleet of EVs can be used for the behind-the-meter optimization. By lowering the peak load, permitting distributed generation, and enabling building self-consumption, the widespread use of V2H and V2B enhances the grid's stability and dependability[5].

V2B does not require additional grid infrastructure or large-scale communication requirements and so is relative easier to implement as compared to V2G. V2B connects the building's energy management to its residents' mobility, with the inherent contradiction that the vehicle is not accessible for energy storage all day and must keep adequate charge for movement. On the other side, vehicle mobility allows for the transmission of stored energy in the battery, perhaps from green sources or a more reliable grid. To fully leverage the V2B capability and increase the building power service efficiency and reliability, the building energy management system (BEMS) must account for these limits as well as the need for flexibility.

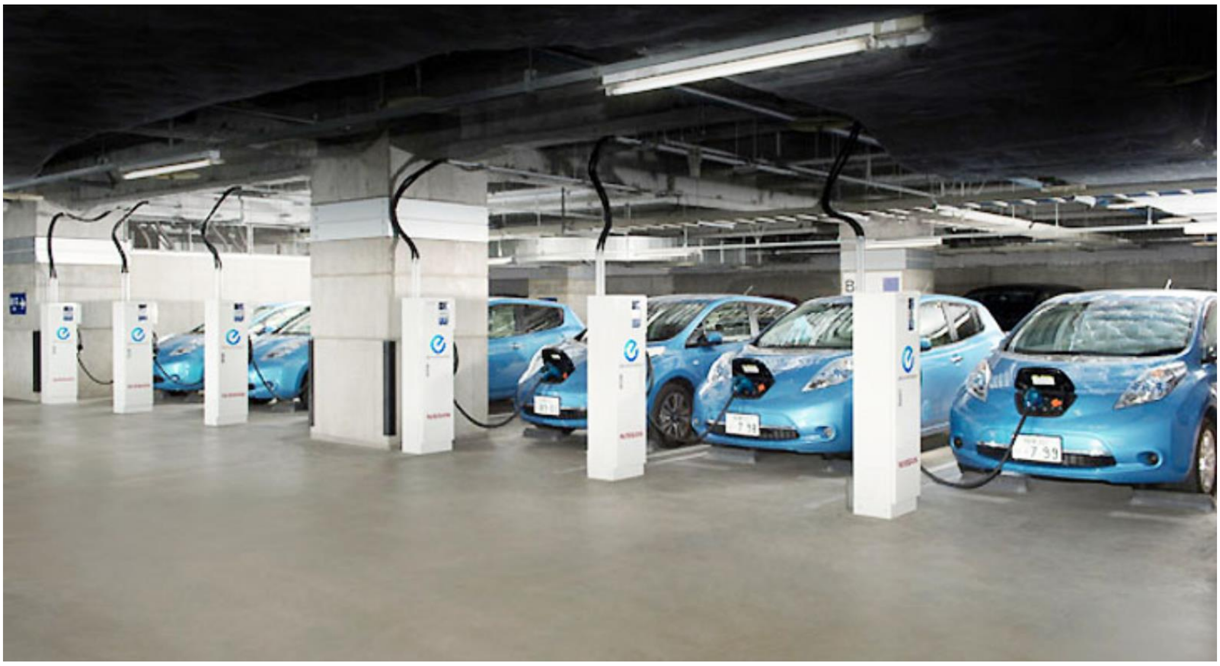

*Figure 2:5 Fleet of Nissan Leafs being used as V2B resources to power an office in Japan*[6]

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[5] Nazari, Shima, Francesco Borrelli, and Anna Stefanopoulou. "Electric vehicles for smart buildings: A survey on applications, energy management methods, and battery degradation." Proceedings of the IEEE 109, no. 6 (2020): 1128-1144.

## 2.1.4 Vehicle-to-Load

Vehicle-to-load (V2L) is one of the simpler applications of V2X, where the EV battery is used to power general independent loads. It allows the EV user to power 220V appliances such as electric drills, induction hotplate, etc. or 12 V devices directly from the EV. For this, some EVs has three pin plugs already available in the EV body while in others an adapter is needed to connect to the charging port of the EV and draw power. It is relatively simple as the inverter inside the EV is used to supply power to the outlets provided.

*Figure 2:6: V2L using an adapter for Hyundai Ioniq 5*[6]

*Figure 2:7: BYD Atto3 V2L adapter*[7]

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[6] Gaton, Bryce, “Vehicle-to-load: The electric cars that will become a mobile power source”, The Driven, November 4, 2021. Vehicle-to-load: The electric cars that will become a mobile power source (thedriven.io)

[7] Svarc, Jason, “Vehicle-To-Load Explained - V2L For Off-Grid And Backup Power”, June 22, 2022. Vehicle-to-load Explained - V2L for off-grid and backup power — Clean Energy Reviews

## 2.1.5 Vehicle-to-Vehicle

In vehicle-to-vehicle (V2V) an EV with bidirectional charging capability is used to charge another electric vehicle. These can be used for the following,

- To power isolated vehicles as emergency backup.
- Share power at charging stations. Here the vehicles are not directly connected to each other. Instead both of them are connected to the charging station. The goal here is to charge EVs while not exceeding the total power capacity of the charging station, i.e. ‘load sharing’ among the EVs.

*Figure 2:8: V2V charging*[8]

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[8] Krishnan, Sibi, “Vehicle to Vehicle (V2V) charging: EV as a power source”, Get Electric Vehicle, August 29, 2018. Vehicle to Vehicle (V2V) charging: EV as a power source – Get Electric Vehicle

# Chapter 3. Vehicle-to-Everything Applications

As mentioned in Chapter 1, V2X has a wide range of applications, such as V2G, V2H, V2B, V2V, V2L etc. Each of the above applications can again be configured to provide a range of services which would be explored in this chapter.

## 3.1 Vehicle-to-Grid

The key feature of V2G is that it uses an existing asset which is the EV battery and provides it the capabilities of a similarly rated grid connected stationary energy storage unit. So technically speaking, a V2G EV can provide all services which can be provided by any other storage unit. While an individual EV may not have the necessary quantum of energy to significantly benefit the grid by itself, aggregating a large number of EVs to a virtual power plant (VPP) can act a substantially large energy storage unit. So, depending on the aggregation size and the control abilities, V2G enabled EVs can provide services both to the transmission network, distribution network and microgrids. The details of the services have been explained below.

### 3.1.1 Peak shaving and load levelling

The electrical load of any network is uneven with peak periods and off-peak periods, and the grid infrastructures are designed to accommodate the peak loads. However, for other durations of the day the grid infrastructure is under-utilized. The cost of the grid infrastructure is passed on to the customers in the form of tariffs.

EVs with V2G can be used optimally manage and shape the load curve of the network to ensure that the grid infrastructure is well utilized. Here, a central control center in cooperation with the electrical distribution utility would design a target load curve. Based on the deviation of the actual load from the target load curve, the charging or discharging of the EVs would be optimally controlled as shown in Figure 3:1. This would help the distribution utility in ensuring that the grid infrastructure is not overloaded and is efficiently utilized. At the same time, as the peak loads would be reduced, this also puts a downward pressure on the energy prices, as the use of costly peak generators to meet the peak demand would be reduced. This can lead to reduced energy prices which would again be reflected as reduced tariffs for the consumer. Also, depending on the business model and contracts with the EV users, they would be accordingly compensated for the peak shaving and load levelling service provided.

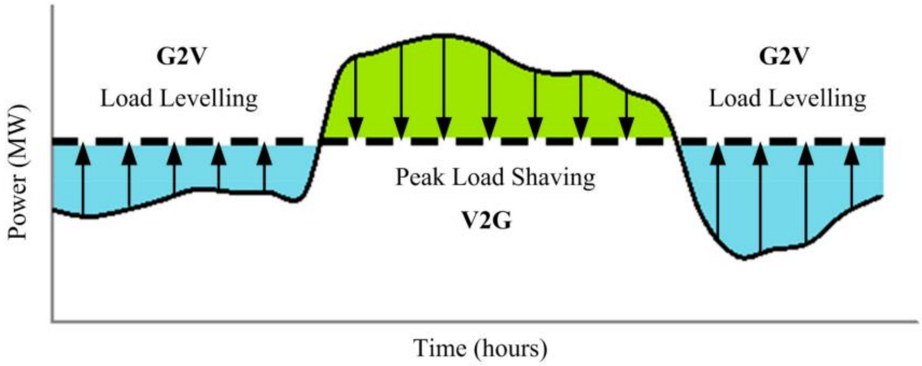

*Figure 3:1: Illustration of peak shaving and load levelling [9] (G2V:Grid-to-vehicle and V2G: Vehicle-to-grid)*

### 3.1.2 Congestion management

All components that make up the electrical grid have physical limits to the amount of electricity it can carry. Congestion occurs when the infrastructure in the grid do not have the physical capacity to transport the required amount of power. Congestion management is used to effectively manage the network such that the operating constraints are not violated. Different strategies are being explored by grid operators to efficiently manage congestion. These include demand response, generator rescheduling, modification in network topology, or even installation of compensation devices such as flexible AC transmission system devices.

One of the promising options to address the issue of network congestion, is to use the connected flexible demand (EV charging/ ACs etc.) to adjust their load based on the network congestion. However, there needs to be financial incentives for prosumers to adjust their loads. This can be either through time based tariffs to have behind-the-meter optimization. Recently however independent flexibility markets have been piloted across the world, few of which as given below[10],

- Sthlmflex in Sweden
- IntraFlex in the UK
- NorFlex in Norway

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[9] Tan, Kang Miao, Vigna K. Ramachandaramurthy, Jia Ying Yong, Sanjeevikumar Padmanaban, Lucian Mihet-Popa, and Frede Blaabjerg. "Minimization of load variance in power grids—Investigation on optimal vehicle-to-grid scheduling." Energies 10, no. 11 (2017): 1880.

[10] Chondrogiannis, S., Vasiljevska, J., Marinopoulos, A., Papaioannou, I. and Flego, G., “Local electricity flexibility markets in Europe”, EUR 31194 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-56156-9, doi:10.2760/9977, JRC130070

- The Grid Operators Platform for Congestion Solutions (GOPACS) in the Netherlands
  As an example the market design of the NorFlex project have been shown in Figure 3:2. Here, prosumers (EVs are one of the viable resources that are allowed to participate) can provide flexibility as a resource which are bought by grid operators as required. The flexibility market facilitates this trading.

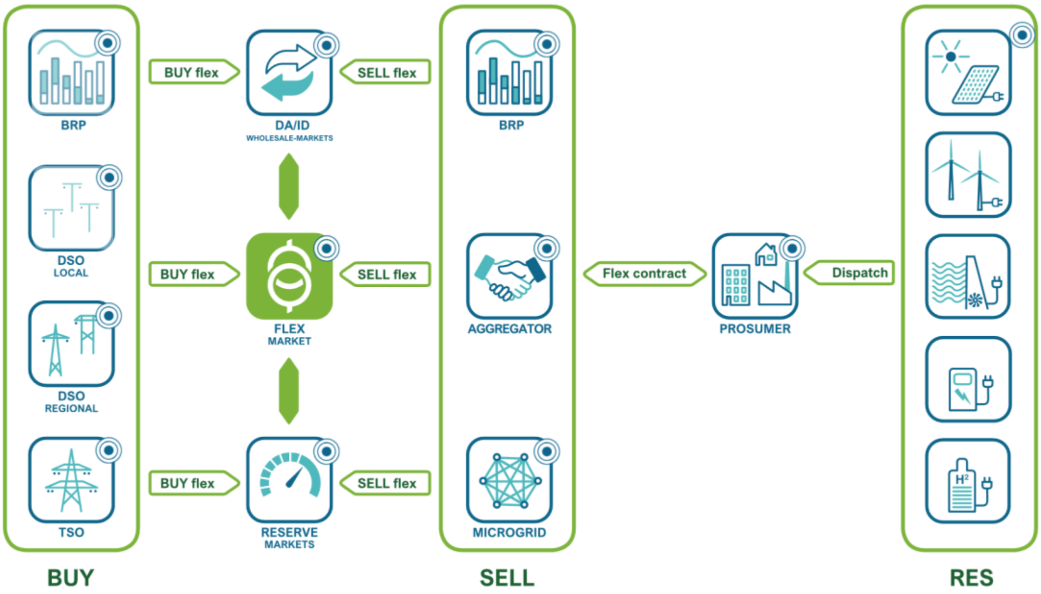

*Figure 3:2: Market design of NorFlex[11]. The prosumers can come into contract with the flexibility market through an aggregator/ balance responsible party (BRP)/ microgrid. On the other ned of the market, the grid operator buys the flexibility resource.*

## 3.1.3 Deferral of network investment

Most distribution networks are designed to cater to the traditional load demands of the locality. The sudden growth of EVs was unforeseen from the electrical distribution operator's point of view. Compared to other loads in the residence, an EV charging load may be several magnitudes higher. Individual loads in a modern residence are typically rated less than 5 kW. Even cumulative residential loads are typically in the range of 1 kW to 7 kW depending on the size of the residence[12]. Comparatively, a single 4-wheeler EV charger can draw 3 kW to 22 kW, varying from model to model. So, large scale integration of EVs can significantly overload the distribution network infrastructure.

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[11] NODES, "Market Design", 2023 [online]. Market Design - NODES (nodesmarket.com)

[12] Chuan, Luo, and Abhisek Ukil. "Modeling and validation of electrical load profiling in residential buildings in Singapore." IEEE Transactions on Power Systems 30, no. 5 (2014): 2800-2809.

Here, controlling the charging (V1G) can help in reducing the stress on the distribution network as shown in the My Electric Avenue in the UK[13]. By optimizing the charging of EVs, the grid infrastructure needed to cater to the peak demand can be controlled, thus reducing or delaying the need for grid upgradation. With V2G, the requirement for grid upgradation can be further reduced, as now the loads in the distribution network can be fed locally from the V2G EVs, further reducing the power drawn from the grid. V2G services are well suited for deferring network investments as network overload events are largely for a comparatively short duration of time per day[14].

The challenge however for such services is that most system operators currently do not have means of valuing the upgrade deferrals. So, while passively the EV users can be benefitted in the form of reduced tariffs, a more active payment mechanism could prove to be more attractive for the EV users. A study by Sandia National Labs determined that the benefits of network upgrade deferral can be as large or larger than more traditional V2G services such as valley filling or spinning reserves[15].

### 3.1.4 Renewable energy integration

One of the major efforts in the decarbonization of the power sector ist the deployment of renewable energy (RE) sources. There has been unprecedented growth of RE sources in the past two decades. The RE resources are characterized by the following[16],

- The generator output is variable because of the primary resource variability.
- The generators are location constrained.
- These are generally non-synchronous energy generation units.

These characteristics create different challenges for the grid operator. Few of these challenges are given in Figure 3:3.

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[13] EA Technology, ‘My Electric Avenue: Intelligent management of electric vehicle charging’. Feb 2016

[14] Pearre, Nathaniel S., and Hajo Ribberink. "Review of research on V2X technologies, strategies, and operations." Renewable and Sustainable Energy Reviews 105 (2019): 61-70.

[15] Eyer, James M. Electric utility transmission and distribution upgrade deferral benefits from modular electricity storage: a study for the DOE Energy Storage Systems Program. No. SAND2009-4070. Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States), 2009.

[16] Sinsel, Simon R., Rhea L. Riemke, and Volker H. Hoffmann. "Challenges and solution technologies for the integration of variable renewable energy sources—a review." renewable energy 145 (2020): 2271-2285.

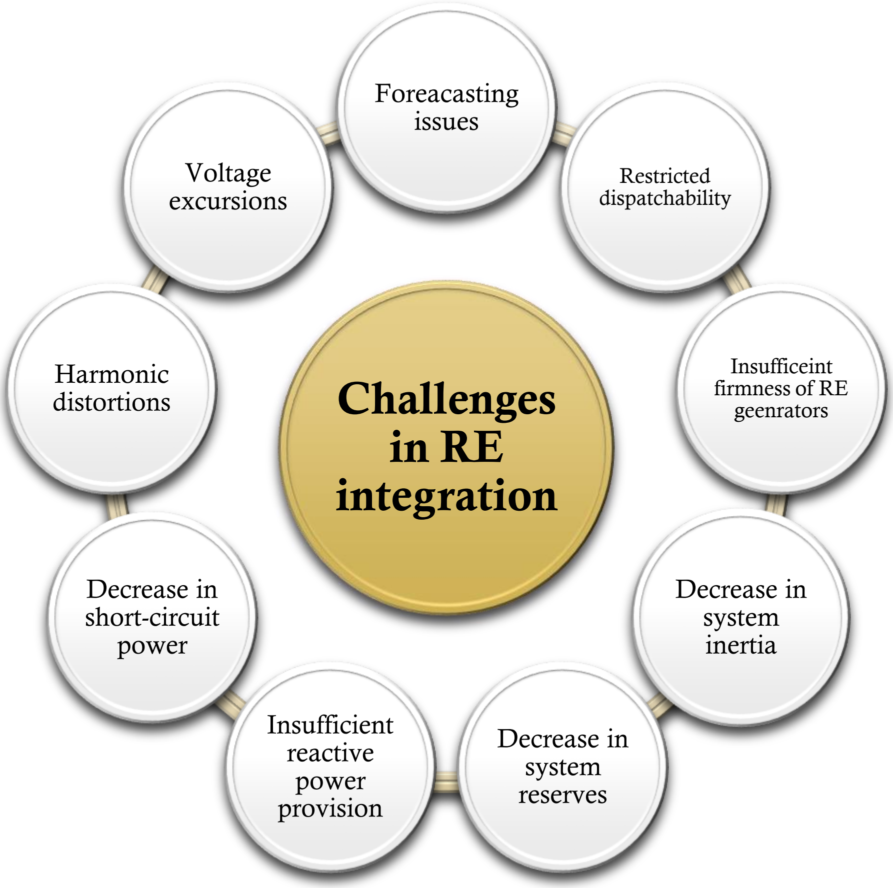

*Figure 3:3: Challenges of high penetration of RE resources*

The controllable nature of V2G enabled EVs can provide solutions to most of the above-mentioned challenges.

- One of the foundational jobs of the electricity operator is to maintain the generation and load balance. For this the operator must be able to anticipate the load profile and schedule the generation accordingly. While traditionally the variability was in the load end, the increased deployment of RE resources has also led to stochasticity in the generation end. This is primarily due to the challenges in accurate forecasting of RE generation and the restrictions in its dispatchability. However, the controllable nature of EVs makes them a viable resource for grid operators to maintain the energy balance in the system. As an example, Vattenfall, an energy company in Netherlands which owns and operates wind power plants and EV charging stations along eighty charging stations owned by different Dutch municipalities have adopted a system to transition EV charging to 100% fossil fuel free. Using this approach, the charging power of the EVs is determined by the amount of energy produced by renewables. As solar and wind are variable resources, so the amount of energy generated by them fluctuates with the weather conditions. For higher spells of wind and solar generation the EVs are charged at their maximum rated speeds, however, for lower supply scenarios the charging speed is reduced temporarily. This is achieved as the algorithm links the charging stations to the balancing market, where the amount of electricity generated and consumed is precisely monitored. Every 15 minutes the charging software checks the availability of energy and adjusts the capacity of the charging stations accordingly[17].

- The lack of controllability over the generation of the RE resources also means that they are infirm. Firmness of RE generation implies that the power generation from the RE resources can be maintained at the committed level for a period of time. Firming options for RE resources include options such integration with conventional generators, energy storage units and other retailer portfolios[18]. Here, instead of conventional storage units, V2G and even second life EV batteries can be integrated to provide such firming supports[19].
- The role of EVs in maintaining system frequency have been discussed in detail in Section 3.1.7. Similarly the role of EVs in providing reactive power have been discussed in Section 3.1.6.

### 3.1.5 Balancing services

The generation and load balance is achieved through multiple energy auctions across different time schedules where generators and demands provide their bids. In most countries, the intra-day balancing is achieved through energy markets. These markets provide a common platform for generators and consumers. The energy prices at these markets can be volatile and so small retail consumers generally do not participate in the market. Instead, an energy retailer (generally DISCOMs in case of India) manages their exposure to the market price volatility using different hedging strategies[20] and provide the customers energy at a fixed rate. Battery storage units have been started to be used as physical hedging units as demonstrated by the University of Queensland

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[17] Vester, Niels V. “Smart charging stations for a more sustainable grid”, Vattenfall, 2020. https://group.vattenfall.com/press-and-media/newsroom/2020/smart-charging-stations-for-a-more-sustainable-grid

[18] Bruers, Matt, “Firming renewables: A commercial perspective”, presented in Wind Energy Forum 2019, Melbourne, 2019, https://assets.cleanenergycouncil.org.au/documents/events/event-docs-2019/WIF19/Matt-Bruers-UPDATE.pdf

[19] Kamath, Dipti, Siddharth Shukla, Renata Arsenault, Hyung Chul Kim, and Annick Anctil. "Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications." Waste Management 113 (2020): 497-507.

[20] Boroumand, Raphaël Homayoun, Stéphane Goutte, Simon Porcher, and Thomas Porcher. "Hedging strategies in energy markets: The case of electricity retailers." Energy Economics 51 (2015): 503-509.

using a 1.1MW/2.15MWh battery[21]. As V2G is technically similar to battery storage units, they can also be used in provision of similar balancing services.

While retail customer generally do not directly participate in the energy markets, Octopus Energy, which is an energy retailer in the UK have recently released a product 'Agile Octopus' where the tariff for the customers is directly linked to the real time electricity prices. Their experience has shown that EV users are highly responsive to the real time price with EV users reducing the peak time energy consumption by almost 47%. The EV users at the same time saved around £132 per year as compared with Octopus' standard tariff and £338 compared to the standard variable tariffs of the Big 6 energy suppliers in the UK[22].

The addition of renewable energy generation has added to the volatility in the market prices[23]. As EV charging is controllable, with V2G even capable of acting as a generator, they can help in providing balancing services to the energy operator.

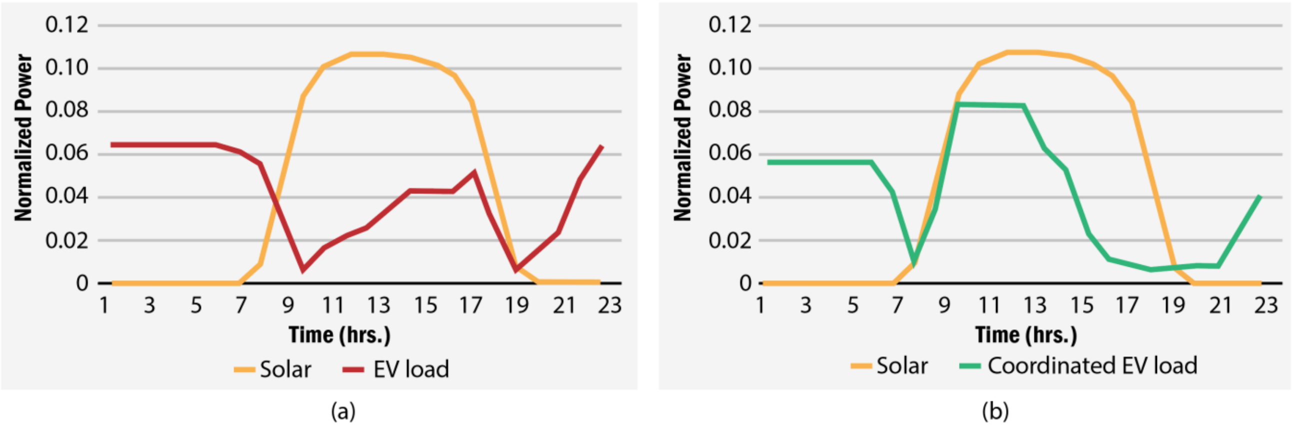

*Figure 3:4: Normalized EV charging profiles with PV system shown for (a) uncoordinated charging and (b) coordinated charging[24] (values in y-axis have been normalized such that values of the 24h sum to 1).*

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[21] A. Wilson, D. Esterhuysen, and D. Hains, "The business case for behind-the-meter energy storage," The University of Queensland, Brisbane, 2020. Accessed: 7/10/2020. https://sustainability.uq.edu.au/files/11868/EPBQtyRptq12020.pdf

[22] Cook, Charlie, "Octopus EV – Tariffs for charging and using smart charging (Ohme cable and V2G)' presented at the Connected Automated Mobility, Milbrook, Bedfordshire, 2019. https://www.cenexcam.co.uk/seminars/session/2019-day-2-hall-5-v2g-business-case.

[23] Ciarreta, Aitor, Cristina Pizarro-Irizar, and Ainhoa Zarraga. "Renewable energy regulation and structural breaks: An empirical analysis of Spanish electricity price volatility." Energy Economics 88 (2020): 104749.

[24] International Renewable Energy Agency, "Innovation landscape brief: Electric-vehicle smart charging," IRENA, Abu Dhabi, 2019

### 3.1.6 Reactive support

One of the critical requirements for maintaining system health is the availability of adequate reactive power reserve. Usually preferred to be generated locally in the distribution network, the network operators often make significant investments in procurements and installation of reactive power compensation devices, such as capacitor banks, synchronous condensers etc. With addition of distributed energy resources such as solar and wind, the control of voltage in the distribution utilities have been more challenging[25].

V2G DC EV chargers can be configured to enable four quadrant operation and help in reactive power compensation for the network[26]. The four-quadrant operation of DC chargers enables them to provide reactive support irrespective of whether the charger is being used for charging an EV. The topology of a bidirectional EV charger would need minimal changes to make it capable of providing reactive support[27]. The quantum of reactive support is capped by the rated capacity of the charger and the EV charging active power load. Further, as the DC-link capacitor is enough to provide reactive power to the network, without necessitating the need of the EV battery, there is no degradation on the life of the EV battery.

### 3.1.7 Frequency support

While the grid operator schedules their generation to match the load for all time periods, there is always minor deviations from the expected load profile. This mismatch in active power is reflected in the frequency of the grid. In the Indian electric grid as per the latest Draft Indian Grid Code 2022, the frequency should nominally lie in a narrow band between 49.95 Hz and 50.05 Hz[28]. However, mismatches between the supply and demand can occur mainly due to two distinct causes,

- Variability in forecasts of both generation and loads.
- Sudden loss of large amount of generation or demand due to contingency in the system such as loss of generator, tripping of transmission line etc.

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[25] Sun, Hongbin, Qinglai Guo, Junjian Qi, Venkataramana Ajjarapu, Richard Bravo, Joe Chow, Zhengshuo Li et al. "Review of challenges and research opportunities for voltage control in smart grids." IEEE Transactions on Power Systems 34, no. 4 (2019): 2790-2801

[26] Mehboob, Nafeesa, Mauricio Restrepo, Claudio A. Canizares, Catherine Rosenberg, and Mehrdad Kazerani. "Smart operation of electric vehicles with four-quadrant chargers considering uncertainties." IEEE Transactions on Smart Grid 10, no. 3 (2018): 2999-3009.

[27] Falahi, Milad, Hung-Ming Chou, Mehrdad Ehsani, Le Xie, and Karen L. Butler-Purry. "Potential power quality benefits of electric vehicles." IEEE Transactions on sustainable energy 4, no. 4 (2013): 1016-1023.

[28] CERC, "Draft Indian Electricity Grid Code Regulations 2022." Jul. 07, 2022

To maintain the stability and security of the network, different ancillary services have been designed.

- Inertia services to slow the rate of change of frequency
- Regulation services to mange the variations in frequency during normal operation.
- Contingency services (Primary, secondary and tertiary reserves) to maintain and restore the system frequency post a contingency event.

Figure 3:5 shows how the different services help maintain the system frequency.

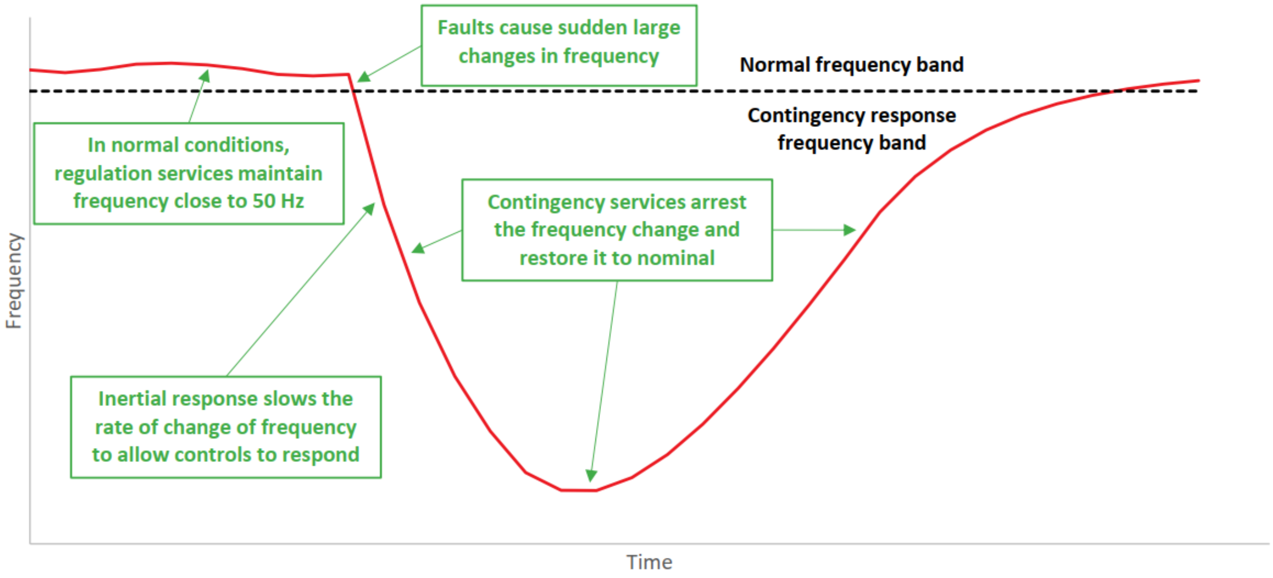

*Figure 3:5: Frequency support services*[29]

### 3.1.7.1 Frequency Regulation Service

The role of frequency regulation service is to maintain the system frequency within pre-specified frequency bands during normal operation and is one of the ancillary services procured by the system operators generally through energy markets. Frequency regulation is the injection or withdrawal of active power by resources in response to regulating signals sent by the system operator or based on local frequency deviations from the nominal value, as directed by the grid operator in the region.

The controllable and fast-acting nature of EVs also lends itself suitable for providing frequency support services. Frequency regulation services from electric vehicles has been demonstrated to

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[29] Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, “The A to Z of V2G: A comprehensive analysis of vehicle-to-grid technology worldwide”, Jan 2021

be technically feasible in different studies around the world[30,31]. The potential of revenue earned from provision of regulation services is however dependent on different factors such as the regulation market prices, service provision hours, bid capacity, power capacity of charger etc[32].

### 3.1.7.2 Inertial Response from EVs

The rate of change of frequency (RoCoF) in power system after a disturbance is arrested by the inertia of the system. The system inertia is the kinetic energy stored in the system due to the rotating masses of the synchronous generators. Nowadays synchronous generators (SGs) which are the main source of inertia support in conventional power grids are being substituted by renewable energy source (RES) generators. Thus, modern power systems with RESs have lower inertia in comparison to conventional power systems that are dominated by synchronous generators. The inertia of power system can be imitated by exploiting the stored energy in existing system (e.g., EVs).

As any difference in the generation/load balancing at one point in the system will be reflected as a change in frequency of system, accordingly, the correlation between generated power, load power, inertia and damping powers and frequency change can be expressed by the well-known swing equation as:

$$\Delta P_m - \Delta P_L = 2H_{SG} s\Delta f + D_{SG}\Delta f$$

where, $\Delta P_m$ and $\Delta P_L$ are the change in power of generator and load respectively, $H_{SG}$ is the inertia of the system, $D_{SG}$ is damping coefficient and $\Delta f$ represents the frequency deviation of system. The dynamic structure of the Synthetic inertia system based on ESS shown in Figure 3:6 could virtually mimic the desirable inertia power during contingencies for the low-inertia modern power grids. The virtual swing equation equation that describes this power can be identified as follows:

$$\Delta P_{imitated} = H_{VI}\frac{d\Delta f}{dt} + H_{VI} s\Delta f + D_{VI}\Delta f$$

$H_{VI}$, $D_{VI}$ are gain of synthetic inertia and synthetic damping respectively. According to the virtual swing equation and by using EV's batteries as energy storage system in the modern power system, the inertia emulation technique can be well described by the analogy between conventional synchronous generators and the batteries of EVs as shown in Figure 3. Where, $H_{VI}$ and $D_{VI}$ denote

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[30] Thompson, Andrew W., and Yannick Perez. "Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications." Energy Policy 137 (2020): 111136.

[31] Thingvad, Andreas, Sergejus Martinenas, Peter Bach Andersen, Mattia Marinelli, Ole Jan Olesen, and Bjoern E. Christensen. "Economic comparison of electric vehicles performing unidirectional and bidirectional frequency control in denmark with practical validation." In 2016 51st International Universities Power Engineering Conference (UPEC), pp. 1-6. IEEE, 2016.

[32] Calearo, Lisa, and Mattia Marinelli. "Profitability of frequency regulation by electric vehicles in Denmark and Japan considering battery degradation costs." World Electric Vehicle Journal 11, no. 3 (2020): 48.

the inertia and damping coefficients from EV's batteries respectively. From Figure 3:7, the symmetry between synchronous generator and EV's battery can be clearly seen, the energy stored in the battery of EV can play the same role as the kinetic energy stored in synchronous generator for inertial support.

However, sub-second reactions (contingency support) may present a challenge for some V2G equipped EV brands.

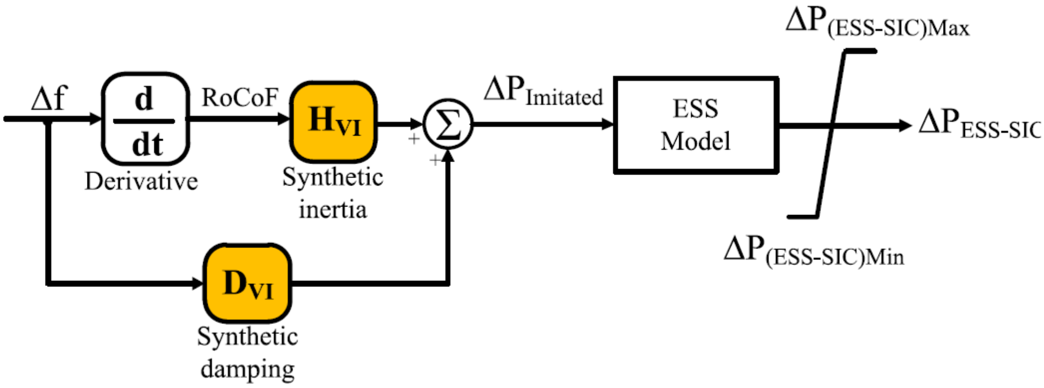

*Figure 3:6: Control architecture for inertial response*[33]

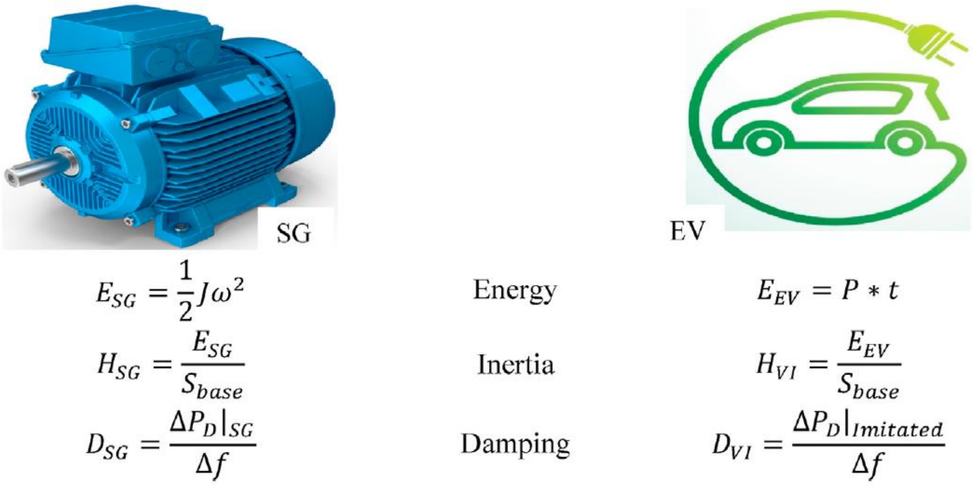

*Figure 3:7: Analogy between synchronous generator and V2G*[33]

### 3.1.8 Demand Response Services

Demand response is a change in electricity consumption by consumers to keep the supply and demand of electricity in balance. Demand response includes a wide variety of actions that reduce the demand for electricity during peak hours and increase the demand for electricity during valley

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[33] Gaber Magdy et al., A new synthetic inertia system based on electric vehicles to support the frequency stability of low-inertia modern power grids, Journal of Cleaner Production, Volume 297, 126595, 2021

hours and help to avoid a system outage. The batteries of EVs could prove to be a valuable asset in balancing the grid. The valley time and the EV plug-in period are largely contiguous. Valley filling can be achieved by electric vehicles, and the load fluctuation, typically caused by disordered charging, can be avoided. Utilities can manage EVs charging time and rates, gather EVs-detailed meter data and, therefore, implement demand response programs. V2G may behave as a load to the grid, a supplier of electricity to the grid or an energy storage device. EVs with V2G capabilities can make payments while charging batteries from the grid and receive incentives while discharging power to the grid. Thus, V2G technology can facilitate the supply and demand balance by charging during off-peak hours (valley filling) and discharging during peak hours (peak shaving). As an example, the grid operator Pacific gas & Electric  in California conducted a study to determine the potential of EVs as demand response resources in their jurisdiction. As per their estimates, EVs had a demand resource potential of between 31MW and 40MW during 12:00 am and 4:00 am and between 9MW and 13MW during 4:00 pm and 9:00 pm considering their existing EV population of 366,000 EVs [34].

By controlling the charging process and scheduling it for off-peak hours, the system's load profile will be smooth. As a result of this, operation costs and power losses of the system will be decreased. However, coordinated charging behavior of the EVs should be considered. To design a smart charging system where there are large number of EVs, the demand response flexibility of the entire load should be assessed. Additionally, the maximum charging delay that each EV can stand should be determined. Using the demand response capability of the EVs by managing the charging process in both V2G and G2V modes is an effective way to reduce the operational costs of the system and satisfying the electricity demand as well. A central control system is required for EVs that operate in vehicle to grid (V2G) mode, which involves sending power back to the grid. This mode necessitates communication between the utility demand and SOC of the EVs battery. Electric vehicles can act as shiftable loads in charging period and as Distribution Energy sources in the discharging period. Considering EVs as shiftable load, make this concern about the time of the second charging occurs. One way to address this issue is the use of basic timers. In this way, EV owners connect their cars as soon as they arrived home, however, the charging process could be postponed to the other time by considering the cost of electricity. Various rate structures can be used to provide incentives for EV owners to take participate in Demand Response.

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[34] Opinion Dynamics, "PG&E electric vehicle automated demand response study report", 2022, https://www.calmac.org/publications/PGE-EV-ADR-Study-Report_FINALV2.pdf

## 3.2 Vehicle-to-Home

Vehicle-to-home is often considered to be first or the easiest application of V2X, as here there is no coordination requirements among a fleet of vehicles, or with the grid operator. Broadly V2H can be classified into two different categories as mentioned below.

### 3.2.1 Power back-up

Here the batteries in the EV are used to power the home in case of emergencies. It was initially commercialized in Japan as a response to the Fukushima nuclear disaster in 2011, which caused widespread grid reliability issues[35]. It can also be coupled to local RE resources to have a completely off-grid system, where the house is completely powered by renewable energy. However, here it has to be ensured that the property is disconnected from the grid mains as otherwise there may be a backwards flow of power as shown in Figure 3:8

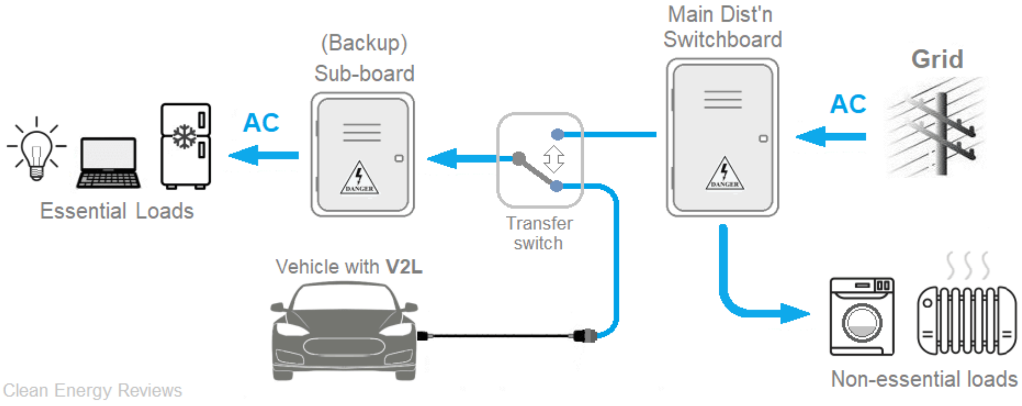

*Figure 3:8: Schematic of using V2H as backup power source*[36]

### 3.2.2 Energy management

By combining V2H with local RE generation or by utilizing time based tariffs, the EV user can reduce the overall operating cost of their residence. The objective here is to minimize the dependence of the residence on energy from the grid. Here by charging the vehicle during off-peak periods or during high RE generation periods the cost of charging the EV is reduced. At the same time, by using the EV to power critical loads during periods when the price of energy from the grid is higher can help the EV user is significantly reducing their costs. The schematic for

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[35] Pearre, Nathaniel S., and Hajo Ribberink. "Review of research on V2X technologies, strategies, and operations." Renewable and Sustainable Energy Reviews 105 (2019): 61-70.
[36] Svarc, Jason, "vehicle-to-load explained – V2L for off-grid and backup power", Clean Energy Reviews, June 22, 2022. https://www.cleanenergyreviews.info/blog/vehicle-to-load-v2l-explained

using V2H for energy management is shown in Figure 3:9. Here the Home Energy Management System (HEMS) controls the EV charging/discharging based on the price of the electricity or the generation of the on-site RE resources.

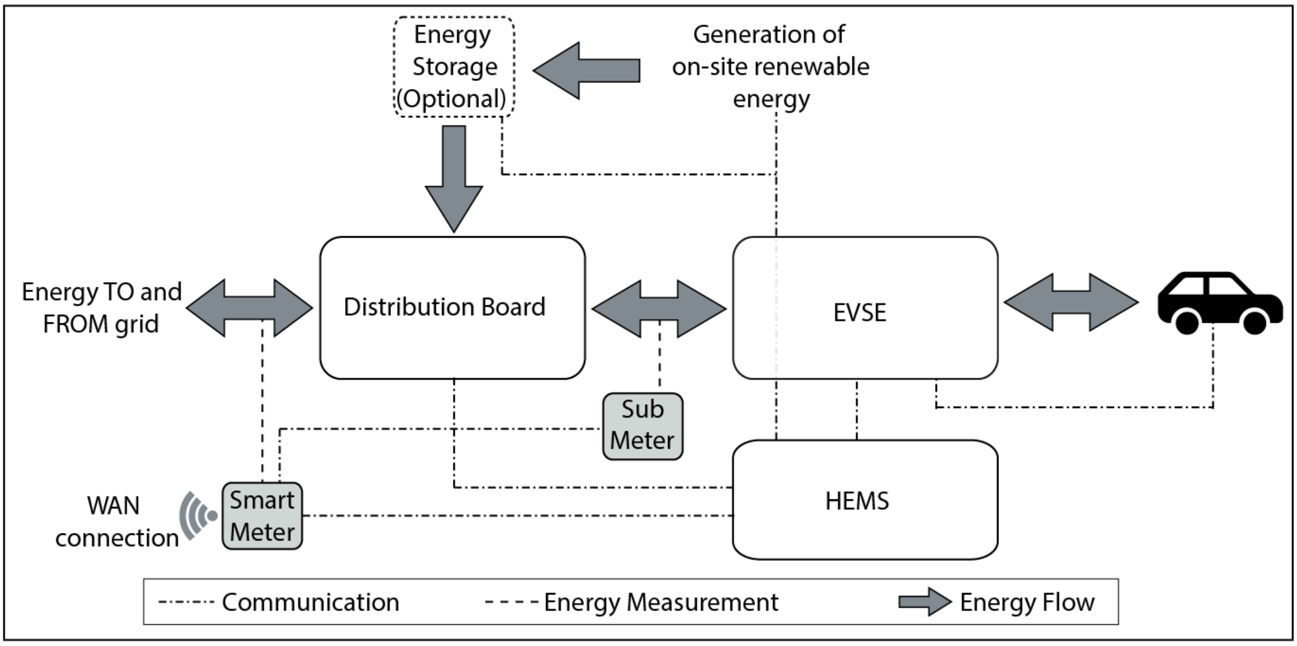

*Figure 3:9: Schematic of V2H application*

## 3.3 Vehicle-to-Building

Vehicle-to-building (V2B) enables the EV batteries for use in behind-the-meter optimizations. The value proposition of V2B lies in the fact that larger industrial and commercial customers in addition to being charged for the energy consumption are also charged for their peak demand, where the customer is also billed for the maximum 15-min peak load[35]. Also, as the number of EVs in a commercial building is higher when compared to a single residential unit, there is higher potential for flexibility provision and higher cost saving opportunities. Similar to V2H the different applications of V2B are described below.

### 3.3.1 Energy management

Instead of a single EV as in V2H, here a fleet of EVs is being used to reduce the overall operating cost of the building. The electricity bill of large customers generally consists of three components: the *energy cost*, the *demand cost,* and the *fixed costs.* The V2G can reduce the energy costs of the building by shifting the energy drawn to off-peak periods. Again by controlling the charging such that the maximum demand of the building is restricted would help in reduction of the demand cost. With V2B, the maximum demand can be further curtailed by discharging the EV batteries when the building has high power consumption[37]. The US Air force demonstrated the capability of EVs in reduction of the building demand in the project at Fort Carson, Colorado[38]. Two specialized Smith electric medium duty trucks with a combined power rating of 95 kW and 125 kWh of energy storage were used in the project. They successfully reduced the demand of the building by 43kW, i.e. $860 per month.

### 3.3.2 Increased RE utilization

The use of V2B for energy management can be further coupled with renewable energy. Here, V2B can facilitate the integration of RE resources. Net zero or nearly net zero energy buildings can be successfully implemented by utilizing V2B as an energy storage unit in conjunction with local RE generation resources[39].

## 3.4 Willingness-to-Pay for V2G

V2G is a novel state of art technology that employs the decentralized battery storage within the EVs to help in grid management. As it utilizes the EVs owned by the general public, so it needs to be examined if the general public is enthusiastic to participate in these services. Further, it also needs to be studied what kind of incentives and remuneration would help in increasing the participation of EV users in V2G. The EV users would only participate in V2G if their advantages of V2G surpasses their disadvantages of V2G. The perception of the EV users to the uses and impacts of participating in V2G is one of the primary drivers for their willingness to participate in these services.

Different survey-based studies have been undertaken to gauge the willingness to pay for V2G applications. One of the earlier studies conducted in 2014, modelled a discrete choice model to study the potential consumer demand for V2G. The study discovered that the EV users place a significant value on the driving flexibility. Reducing the available driving range for the EVs after V2X service from 175 miles (281.63 km) to 75 miles (120.7 km) is equivalent to increasing the

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[37] Nazari, Shima, Francesco Borrelli, and Anna Stefanopoulou. "Electric vehicles for smart buildings: A survey on applications, energy management methods, and battery degradation." Proceedings of the IEEE 109, no. 6 (2020): 1128-1144.

[38] Millner, Alan, Christopher Smith, Erik Limpaecher, Gabriel Ayers, Stephen Valentine, Raymond Paradiso, Victoria E. Dydek, and William Ross. "Plug in electric vehicles and the grid." In 2014 IEEE NewNEB DC Utility Power Conference and Exhibition (NewNEB), pp. 1-6. IEEE, 2014.

[39] Barone, Giovanni, Annamaria Buonomano, Francesco Calise, Cesare Forzano, and Adolfo Palombo. "Building to vehicle to building concept toward a novel zero energy paradigm: Modelling and case studies." Renewable and Sustainable Energy Reviews 101 (2019): 625-648.

price of the vehicle by INR 3,59,366 ($4020)[40]. Similarly, increasing the minimum mandated plug-in time from 5 hr to 15 hr and 20 hr is equivalent to increasing the initial cost of the vehicle by INR 3,92,308 ($4454) and INR 7,49,032 ($8504). Accordingly, 8 different V2G contracts were defined as shown in Table 3.1. The resulting upfront discount needed for the users to participate in these eight different V2G contracts are given in Figure 3:10. From the figure it can be seen that the minimum upfront discount needed for an EV user to participate in Contract H for example is around INR 12,33,120 ($14000). If it is annualized over 8 years and using a 5% discount rate results an annual payment of around INR 1,92,89 ($2190). So, the result concluded that EV users see inconvenience in participating in V2G services if their mobility requirements would be hampered.

*Table 3.1: V2G contract configurations (GMR: minimum range after V2G service, RPT: minimum plug-in time required)*[40]

| Contract term scenario | GMR | RIVI |
|---|---|---|
| A | 75 miles | 5 h |
| B | 75 miles | 10h |
| C | 75 miles | 15h |
| D | 75 miles | 20 h |
| E | 25 miles | 5 h |
| F | 25 miles | 10h |
| G | 25 miles | 15h |
| H | 25 miles | 20 h |

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[40] Parsons, George R., Michael K. Hidrue, Willett Kempton, and Meryl P. Gardner. "Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms." Energy Economics 42 (2014): 313-324.

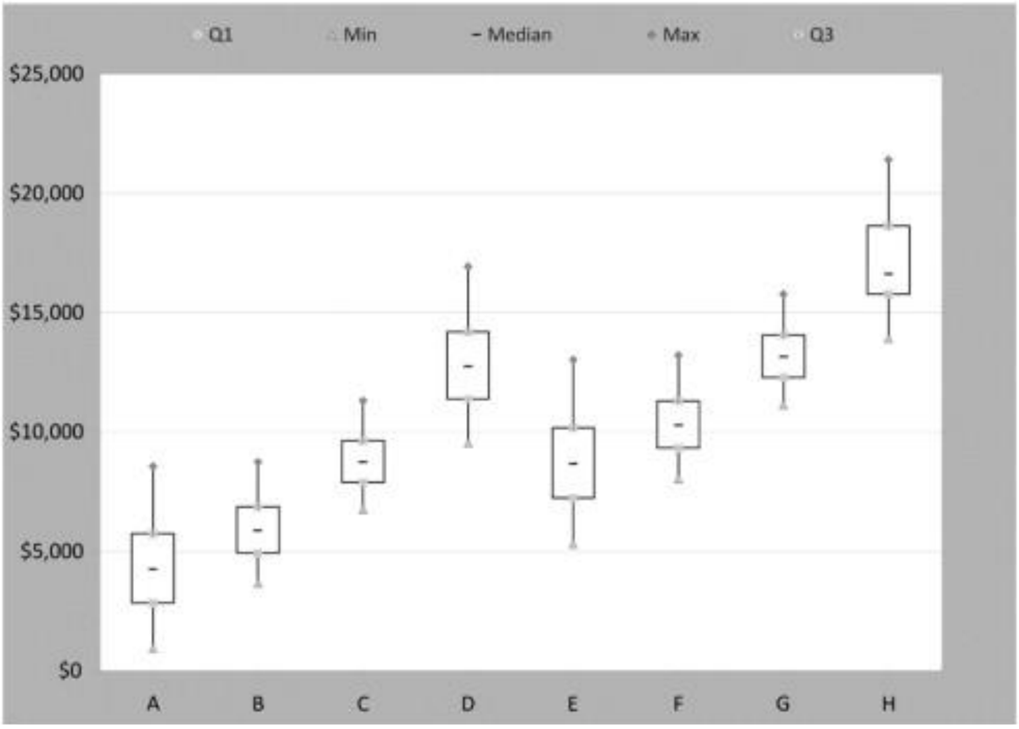

*Figure 3:10: Box and whisker plot for upfront discount on purchase of vehicle for the 8 different V2G contracts*[40]

A similar conclusion was also made by another independent survey based study conducted by Geske *et. al*, who found that 'range anxiety' and 'battery degradation' are the most important determinants of the willingness of users participating in V2G[41,42]. However, they also made a comment that if the are smoothened out, high V2G participation may be achieved even without any remuneration. Of the different V2G services, the survey participant placed the highest value on utilizing V2G for 'reducing the costs of future electricity storage' and 'increasing the share of renewable sources of energy for the use of electric vehicle'.

A Nordic focus group study also highlighted that the focus groups were optimistic about V2G technology, however they brought certain concerns about V2G[43]. The questioned the potential value that V2G can bring to EV users, as they believe that it is of more value to the grid. Further they also questioned if the EV users should even be involved and they rather preferred it to be automated and completely integrated in the charging algorithm itself. They believed that as long as the implementation of V2G does not impact the travel needs of the user, the consumer need

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[41] Geske, Joachim, and Diana Schumann. "Willing to participate in vehicle-to-grid (V2G)? Why not!" *Energy Policy* 120 (2018): 392-401.

[42] OEMs are now providing battery warranty for V2G use, provided the user profile is approved by the respective OEMs.

[43] Kester, Johannes, Gerardo Zarazua de Rubens, Benjamin K. Sovacool, and Lance Noel. "Public perceptions of electric vehicles and vehicle-to-grid (V2G): Insights from a Nordic focus group study." *Transportation Research Part D: Transport and Environment* 74 (2019): 277-293.

not be involved[44]. Further, few participants of the focus group also questioned on how the EV users would be repaid for the increased battery degradation due to V2G services.

To summarize it can be seen that the interest of EV users to participate in V2G services is largely governed by their knowledge and awareness of V2G technology. As long as the users are compensated for the 'expected battery degradation'[45], and their mobility needs are not hampered the EV users are willing to participate in these services[46]. In other words, it would be difficult to entice the EV users to participate in V2G services in lieu of their mobility requirements.

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[44] The focus group is based in the Nordic countries of Denmark, Norway, Sweden, Iceland and Finland, and have higher trust on the grid operators making the decision on using EVs support the grid if and when necessary.

[45] Although battery degradation is a major concern for users participating in V2G services, latest research has shown that V2X optimally scheduled can even help improve battery life. So, once the market is matured enough and people are more aware about V2X the concern about battery degradation is expected to diminish significantly.

[46] Fleet operators run their operations purely on the Total Cost of Ownership. So, these section of EV users are more likely to participate in V2G, purely based on economic performance.

# Chapter 4. Value estimation for V2X

## 4.1 V2X value chain

V2X implementation requires multi stakeholder collaboration and so for its success, the different involved stakeholders need enough financial benefits to stay engaged in this business. Here, V2X is an umbrella term that encompasses different approaches by which additional value can be extracted from the battery storage unit in an EV. So, while determining the value chain for V2X implementation, the value extracted by the entire EV ecosystem needs to be properly accounted for. Even prior to V2X application, different business are involved in practices such as raw material extraction, manufacturing of EVs, chargers, assembly etc. thereby deriving lucrative revenue. The different value streams just for developing and establishing an electric vehicle ecosystem has been given in Figure 4:1. For all of the different identified value streams, a unique business opportunity could be created.

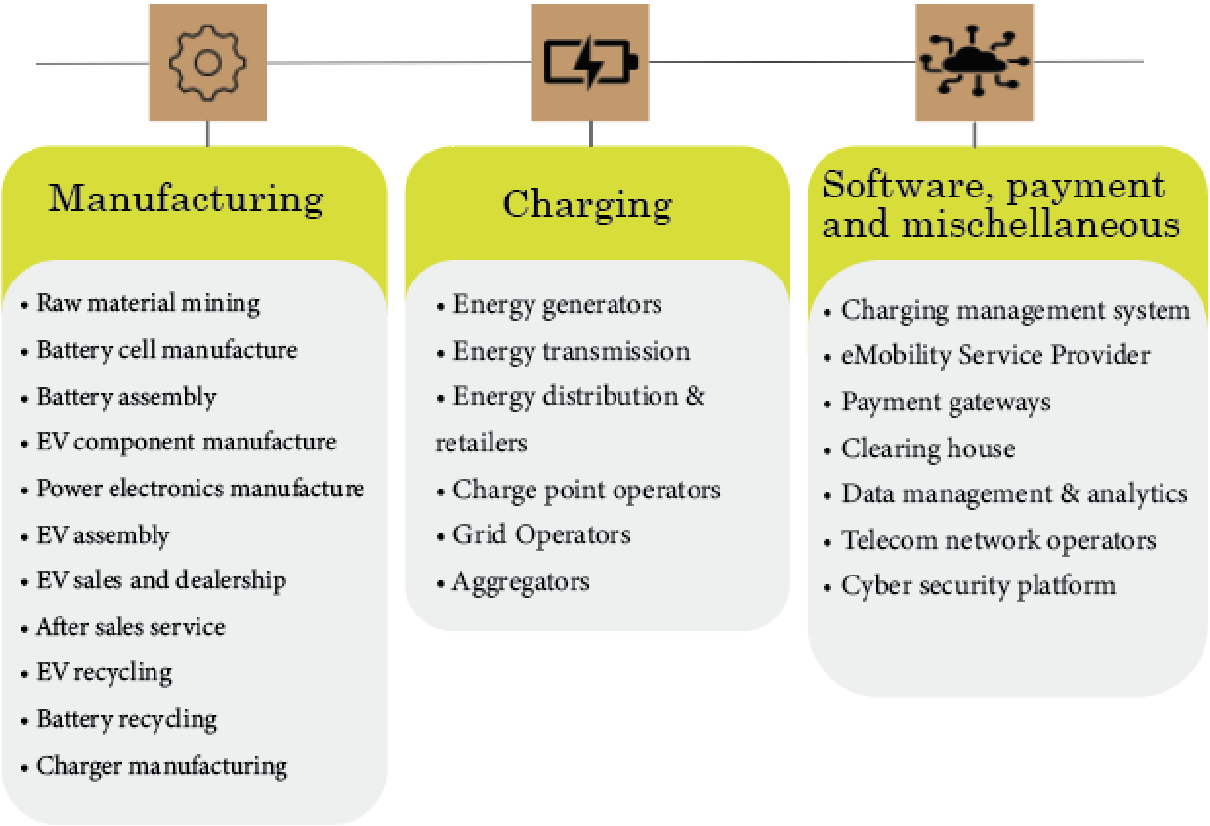

*Figure 4:1: Value stream in electric vehicle ecosystem*

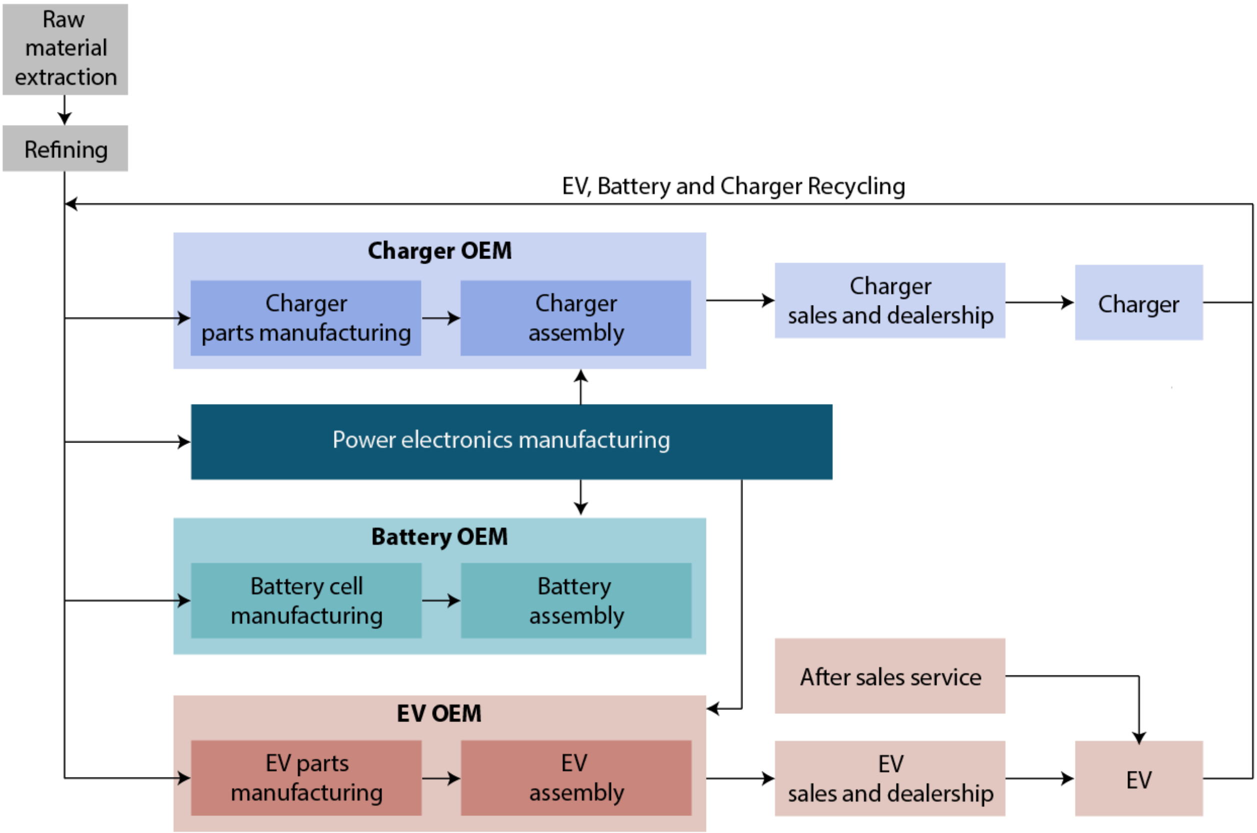

*Figure 4:2: Value streams in EV and EV charger manufacture*

V2X applications further increases the potential value additions that can be made from transitioning to electrified transportation. As the underlying technology of V2X is similar to other lithium-ion battery storage systems (BESS), so technically V2X can also participate in most applications where BESS can be used.

The different stakeholders can derive value at different stages of the V2X application. Stakeholders such as energy generation entities, transmission and distribution utilities, CPOs can extract value directly by sale of energy. The EV users extract value when they get financial benefits (in form of cost minimization or revenue generation) by performing the V2X application. The aggregator and the CMS facilitates this V2X application, enabling them to create revenue opportunities. At the same time the TSO, DSO and market operator acquires a new resource for grid support services, which can help them better manage the grid, thereby leading to value addition. Finally, to facilitate the entire operation a robust and reliable communication network needs to be developed and maintained and thus providing value to telecom operators. The different entities and stages where the stakeholders can extract value using V2G, and V2H have been summarized in Figure 4:3, and Figure 4:4 respectively.

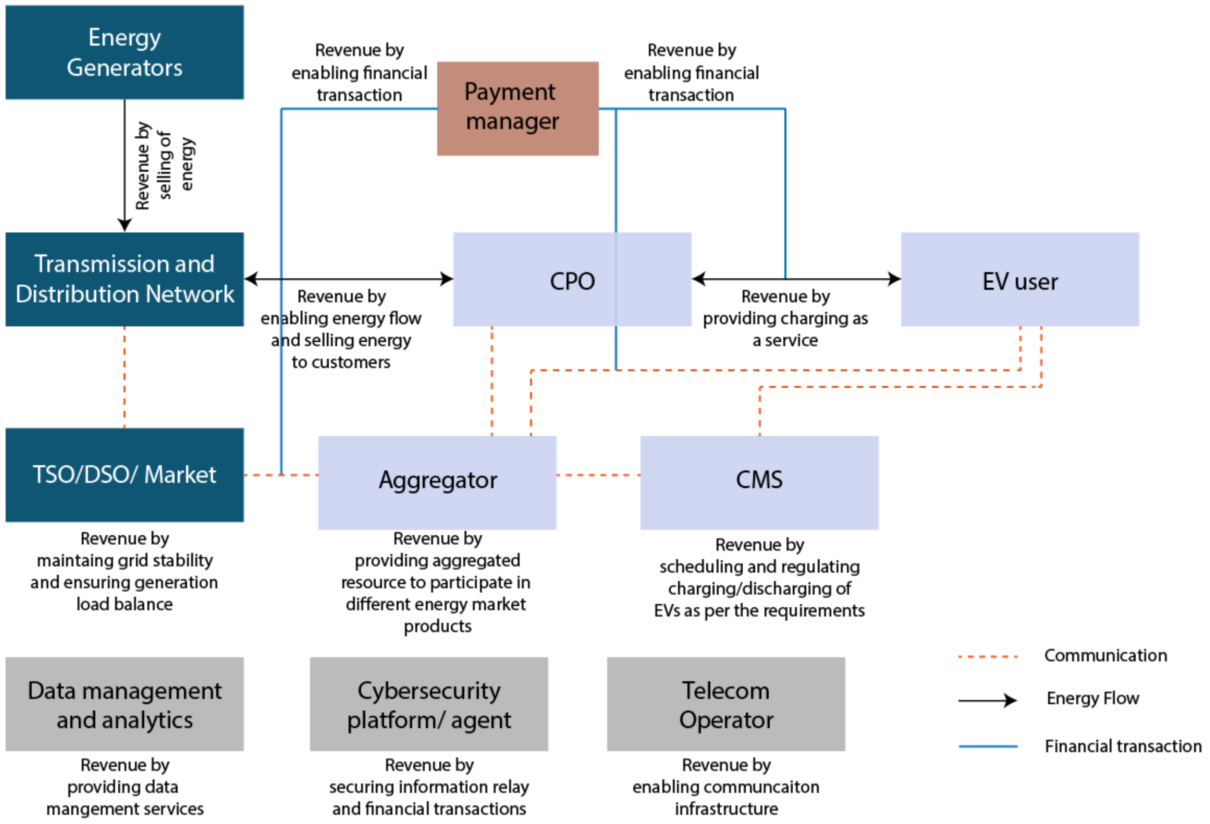

*Figure 4:3: Value chain of V2G application*

A meta-analysis was performed by Thompson and Perez[47], where they identified and estimated the value extraction from V2X services. As per their analysis the potential revenue potential across the different value streams have been shown in Figure 4:5. From the figure it can be seen that there is a wide range of estimations of market value of the different revenue streams, which are dependent on different factors such as the local electrical network, the differing market conditions etc. Hence, claims of universal economic viability of certain V2X applications may be difficult due to market intricacies, local and regional energy technology mix, demand growth etc. However, it can also be seen that applications such as bill management, network deferral and demand response have higher valuations across the different markets, while energy arbitrage, spinning reserve showed themselves to be less lucrative.

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[47] Thompson, Andrew W., and Yannick Perez. "Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications." Energy Policy 137 (2020): 111136.

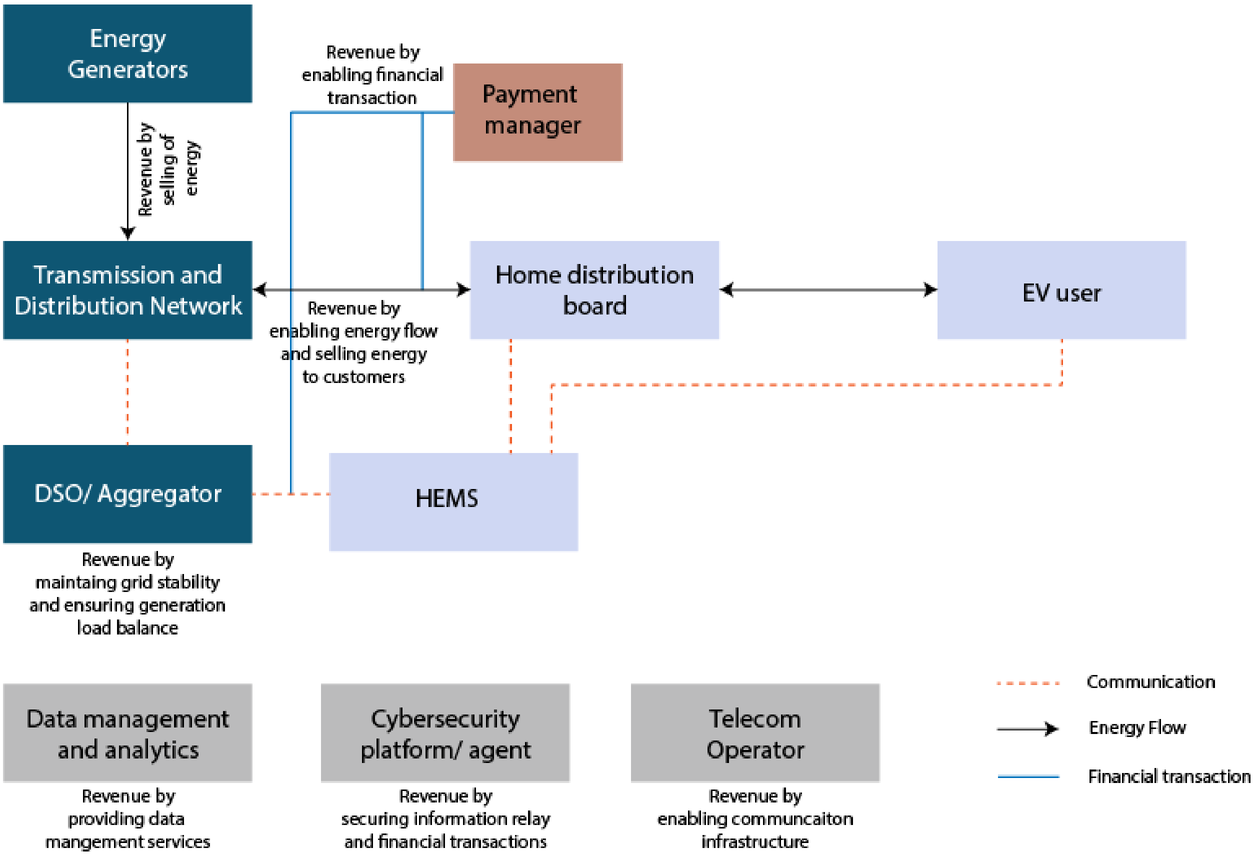

*Figure 4:4: Value chain in V2H application*

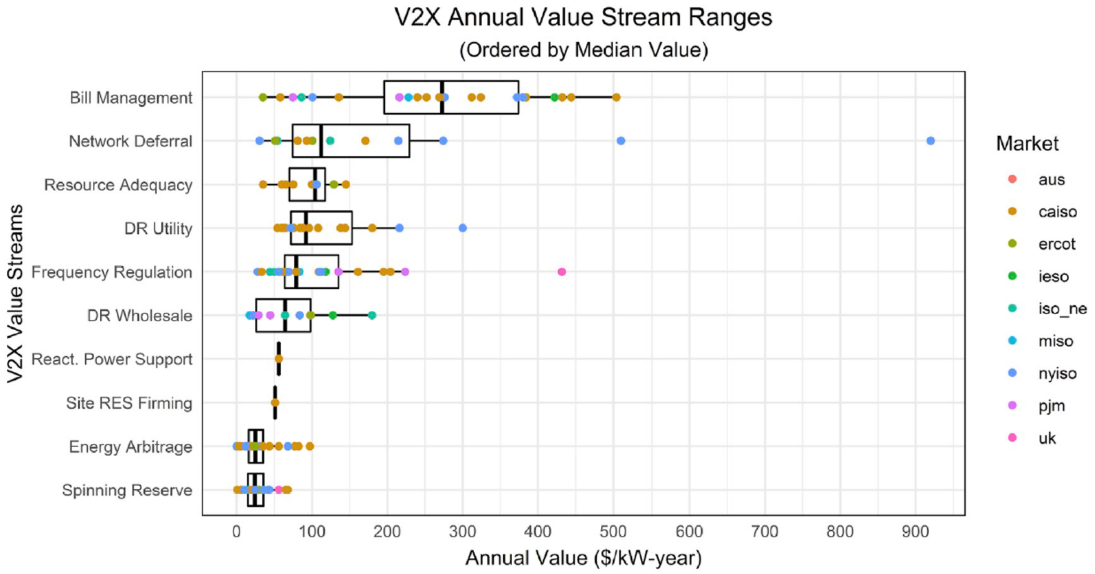

*Figure 4:5: Overall economic potential of V2X value streams. The coloured dots show the expected value for different value streams under different electricity market operators and the box plot show the overall range of value that can be extracted from V2X applications*[47,48]

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[48] ***Bill Management***: Use V2X for reduction of energy and demand charges. Value is added due to cost savings (Applicable for V2B/V2H) ***Network Deferral:*** Use V2X for delaying/reducing the electricity network upgradation requirement in capacity constrained areas (Applicable for V2G/V2B/V2H)

### Valuation of V2X in comparison with BESS

Suppose a player wants to participate in demand response/ancillary service products of the energy market. To achieve this, the player can invest in a utility scale storage unit that would enable them to participate in the different grid products, or he can potentially participate using V2X. As opposed to utility scale storage the total investments that needs to be made by the player is significantly less for the case of V2X services as the player is not paying for the storage itself. They are just investing to creating an enabling system (V2X chargers, communication systems, integration with the market etc.). The storage itself i.e. the EV, is owned and operated by the individual users.

## 4.2 Impact of V2X on Battery Health

Compared to conventional V0G and V1G technologies, battery's operation – charging and discharging – increases considerably in V2X (but highly dependent on the V2X service provided). Due to higher number of charging and discharging, although the battery's life is expected to reduce due to higher rate of degradation, the answer is not that straight forward. In the subsequent sections, the critical reasons for battery degradation will be analysed.

The two avenues of battery aging are

- Calendar aging
- Cycle aging

Calendar aging is the natural loss of life of the battery due to passage of time, and cycle aging is the loss of battery health due to charging and discharging of batteries. So, here the general assumption regarding degradation due to V2X applications is that as the number usage cycles is going to increase the degradation of the battery would increase. Although true, it is not the

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***Resource Adequacy:*** Provide power by discharging of EVs in order to reduce demand, and helping maintain generation-load balance at all periods (Applicable for V2G)
***DR Utility:*** Provide demand response services in response to distribution grid operator signals.
***Frequency Regulation:*** Provide support in maintaining system frequency by participating in frequency regulation services (Applicable for V2G)
***DR Wholesale:*** Provide demand response services in response to electricity market operator signals.
***Reactive Power Support:*** Adjust reactive power provided by EVs and charging stations in response to voltage deviations as recommended by the system operator. (Applicable for V2G)
***Site RES Firming:*** Control EV charging/discharging to firm solar/ wind or other renewable generation resources to improve renewable energy utilization. (Applicable for V2G/V2B/V2G)
***Energy arbitrage:*** Buy electricity during low price hours and sell them during high price hours. (Applicable for V2G)

complete picture. The increased usage of battery would lead to increased 'cycle aging' of the battery. However, the impact on calendar aging maybe interesting.

The different drivers of battery degradation and their impacts have been shown in Figure 4:6. From the figure it can be seen that temperature and SoC levels have a very high impact on the calendar aging of batteries. Regarding cyclic aging the charging rate (C-rate), Depth of Discharge (DoD) and the SoC are the significant drivers. This implies that a battery stored at high SoC levels and temperatures  would face high degradation. By maintaining the SoC of the battery between 30%-50% SoC, the health of the battery significantly improves[49]. While health of the battery is deteriorated with increased charge/discharge cycles, the V2G algorithm can be optimized to help maintain the SoC of the battery within the optimal range. Based on this idea, studies have already shown that optimized V2X implementation can also help in prolonging battery life[75].

The battery's charging schedule determines the effect of bidirectional charging on the battery's health. Dubarry et al. attempted to research the effects on commercial Li-ion batteries if the charging regime is designed to maximise the profit of the EV owner, i.e. selling as much energy to the grid[50]. Their findings demonstrated that the battery health deterioration is more pronounced than it would be without the use of V2G because of the rise in cycle count as well as the rise in DoD of each cycle. According to their investigation, a battery with two V2G cycles each day lost close to 20% of its capacity after five years, whereas a battery without V2G lost only about 10%. However, in this scenario the battery control have been designed to maximize the usage of the battery in order for the EV user to earn maximum revenue.

As previously mentioned, a battery's health also depends on the storage SOC and the DoD of each cycle. A different study investigated the possibility of prolonging battery life by optimising the V2G regime[51]. They calculated the expected degradation of the battery while it is stored at its stored SoC to the degradation of the battery owing to the expected cycle using the discharging algorithm. Only when the degradation caused by discharge outweighed the degradation caused by storage was the battery permitted to be discharged. The scientists were able to decrease the energy capacity fade by 9.1% by adjusting the charge discharge cycle based on the influence on battery deterioration when compared with EV with no V2G.

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[49] Hoke, Anderson, Alexander Brissette, Dragan Maksimović, Damian Kelly, Annabelle Pratt, and David Boundy. "Maximizing lithium ion vehicle battery life through optimized partial charging." In 201

[50] Dubarry, Matthieu, Arnaud Devie, and Katherine McKenzie. "Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis." Journal of Power Sources 358 (2017): 39-49.

[51] Uddin, Kotub, Tim Jackson, Widanalage D. Widanage, Gael Chouchelamane, Paul A. Jennings, and James Marco. "On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system." Energy 133 (2017): 710-722.

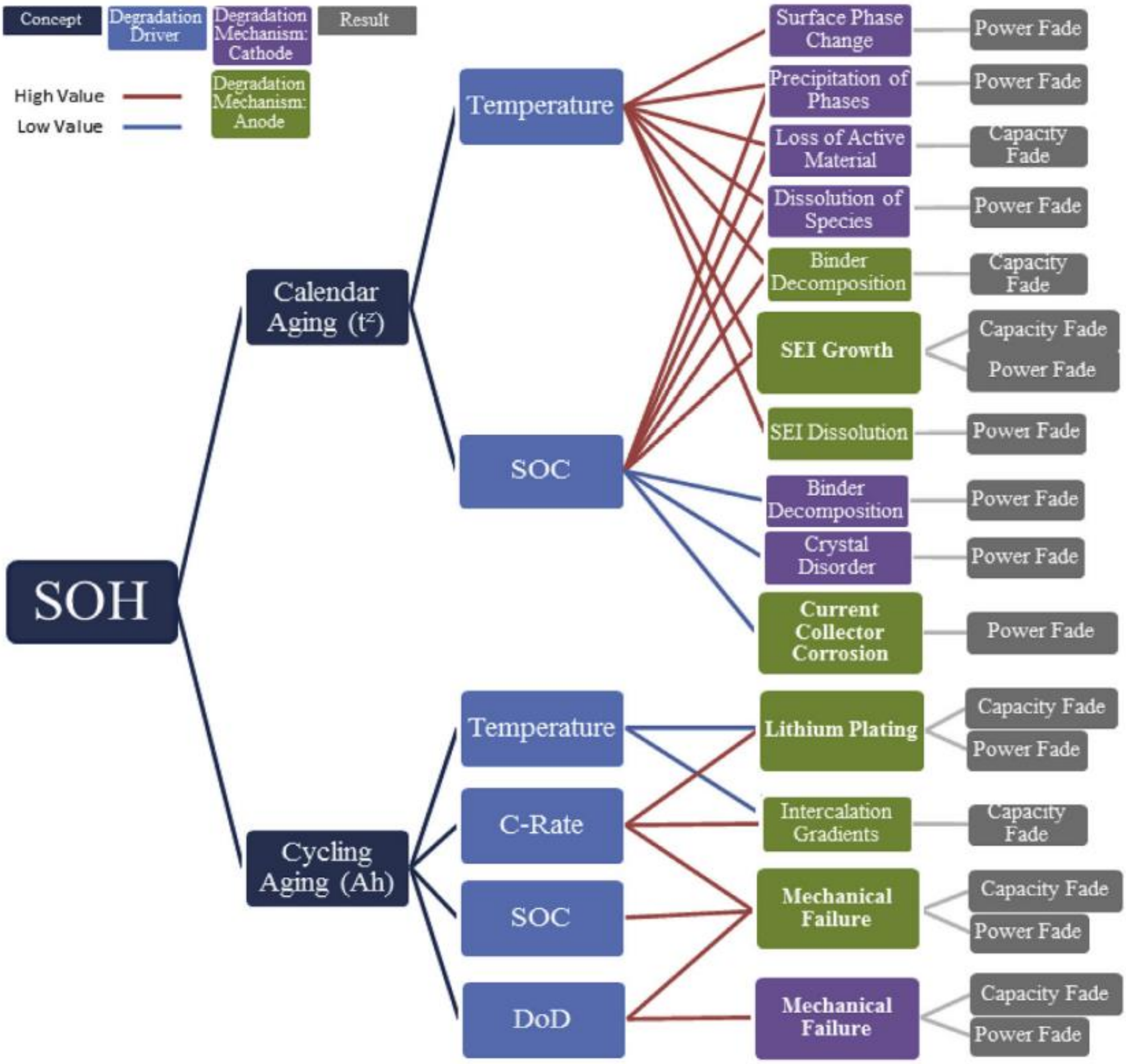

*Figure 4:6: Summary of battery degradation. The flowchart shows links of degradation concepts with degradation drivers.*[52]

So, in essence although V2G would increase the cycle count, but the impact on the battery health is more complicated. The impact on battery health can be minimized and even reversed by optimizing the charge discharge cycle.

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[52] Thompson, Andrew W. "Economic implications of lithium ion battery degradation for Vehicle-to-Grid (V2X) services." Journal of Power Sources 396 (2018): 691-709.

## 4.3 Cost of RE integrated EV charging station

The component wise breakdown of costs for RE installation has been shown in Figure 4:9 and Figure 4:10, from which it can be seen that the major chunk of investment for PV plants is spent on the modules and inverter hardware. However, compared to USA, the prices in India are relatively cheaper. Further the cost of labour i.e., mechanical, and electrical installation is also significantly lower in case of India compared to the USA. The total per kW cost of solar PV installation in India comes around INR 52,000. Similarly, the total per kW cost of wind installation in India comes around INR 70,081.04[53].

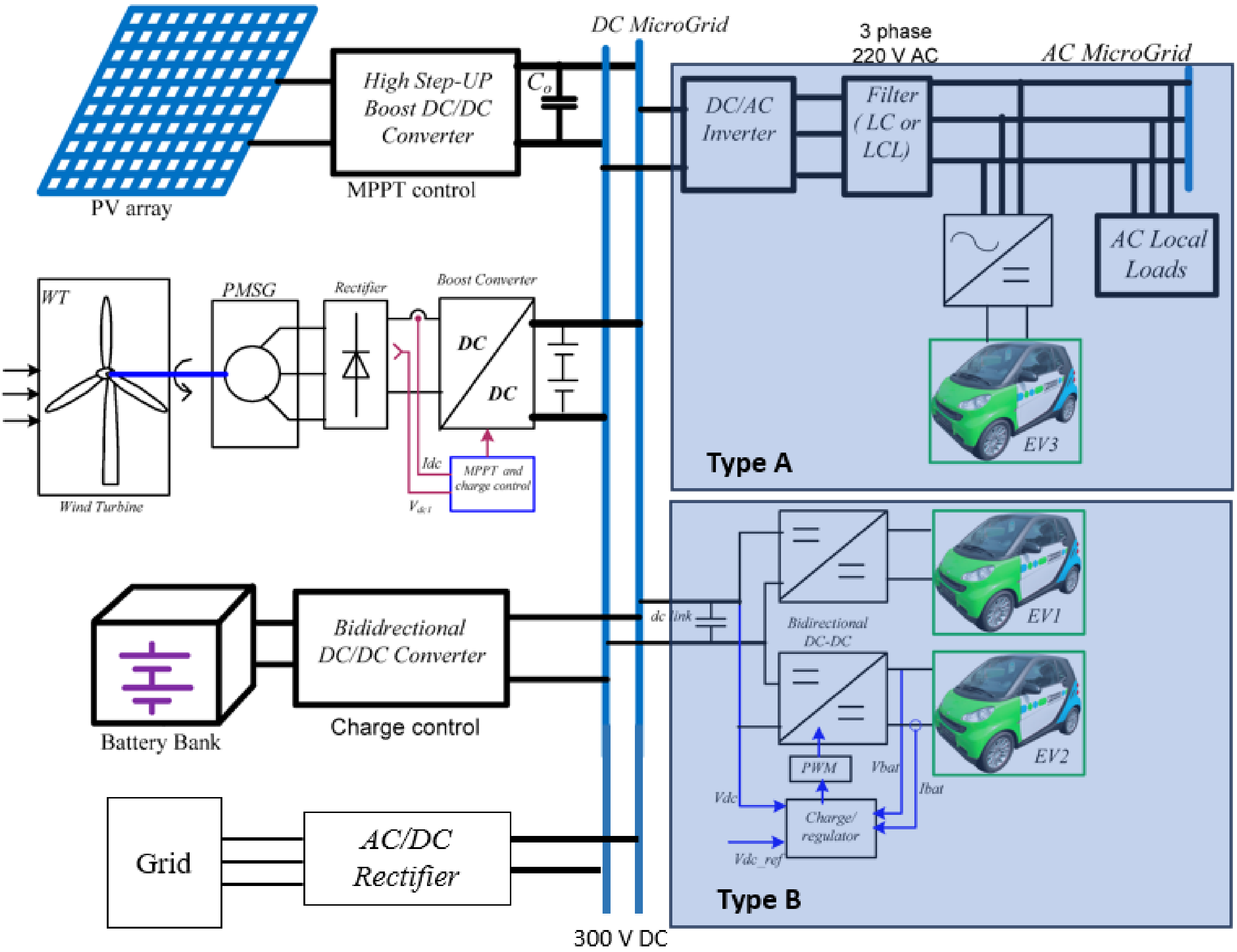

*Figure 4:7: DC microgrid RE integrated EV charging topology[54]*

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[53] The data on the cost of wind installation is for USA. The installation cost in India has been derived based on the ratio of cost of solar installation costs in USA and India. The ratio of cost of solar installation in USA to India is around 1.84.

[54] Sayed, Khairy, Ahmed G. Abo-Khalil, and Ali S. Alghamdi. "Optimum resilient operation and control DC microgrid based electric vehicles charging station powered by renewable energy sources." Energies 12, no. 22 (2019): 4240.

The cost of integration of EV charging with RE plants would then depend on the charging station topology being used. For DC microgrid based EV charging station as shown in Figure 4:7, two different EV charging configuration can be employed. In Type A type configuration, the power from the DC microgrid is first converted to AC power using a DC/AC inverter which is then fed to the EVSE. However, in Type B type configurations, the DC power is directly fed to the EV chargers. The system cost for type B type configurations would be lower as it has fewer converter requirements. In DC microgrid based topologies, the inverter for the solar PV is not required leading to a reduction in total system cost. Comparatively, in AC microgrid based topologies shown in Figure 4:10, an inverter is needed to convert the DC output of the solar PV plant to AC power.

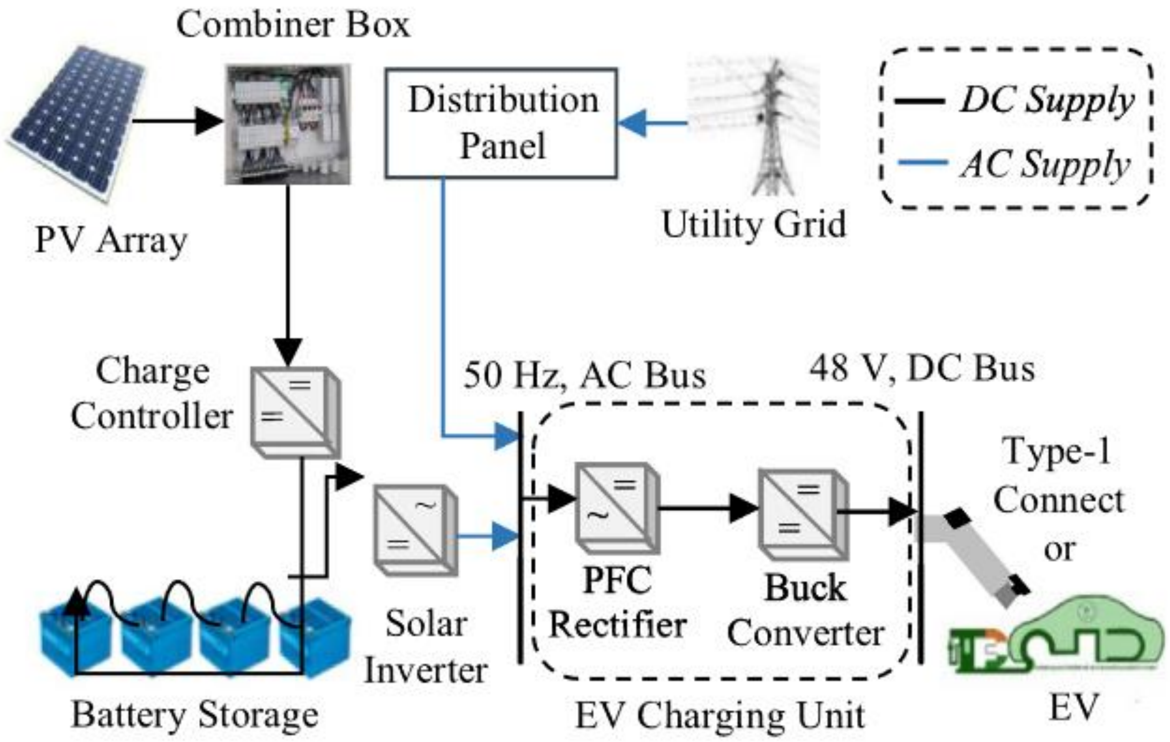

*Figure 4:8: AC microgrid RE integrated EV charging topology*

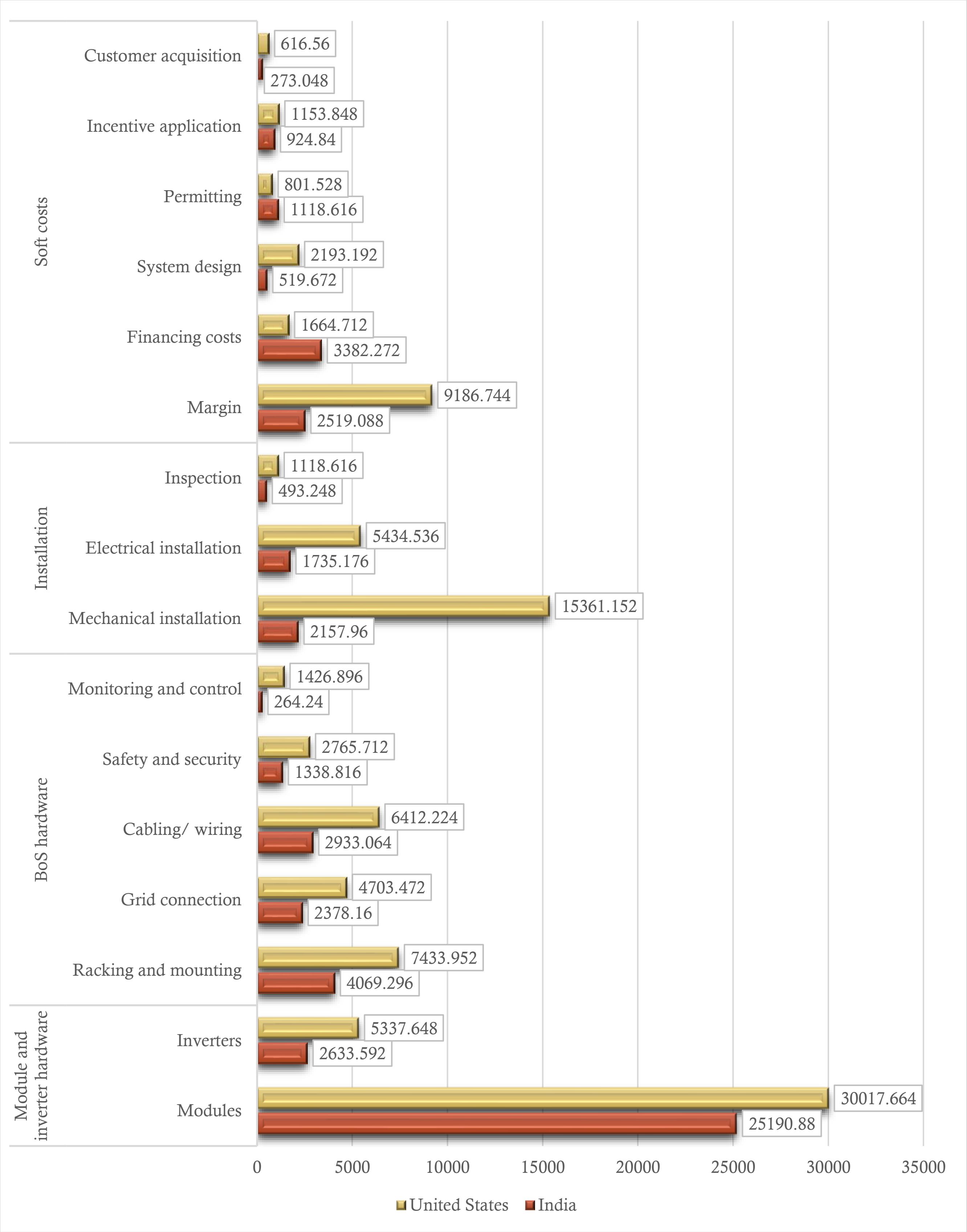

*Figure 4:9: Average cost of installation of installation of PV plant (in INR/kW)*[55]

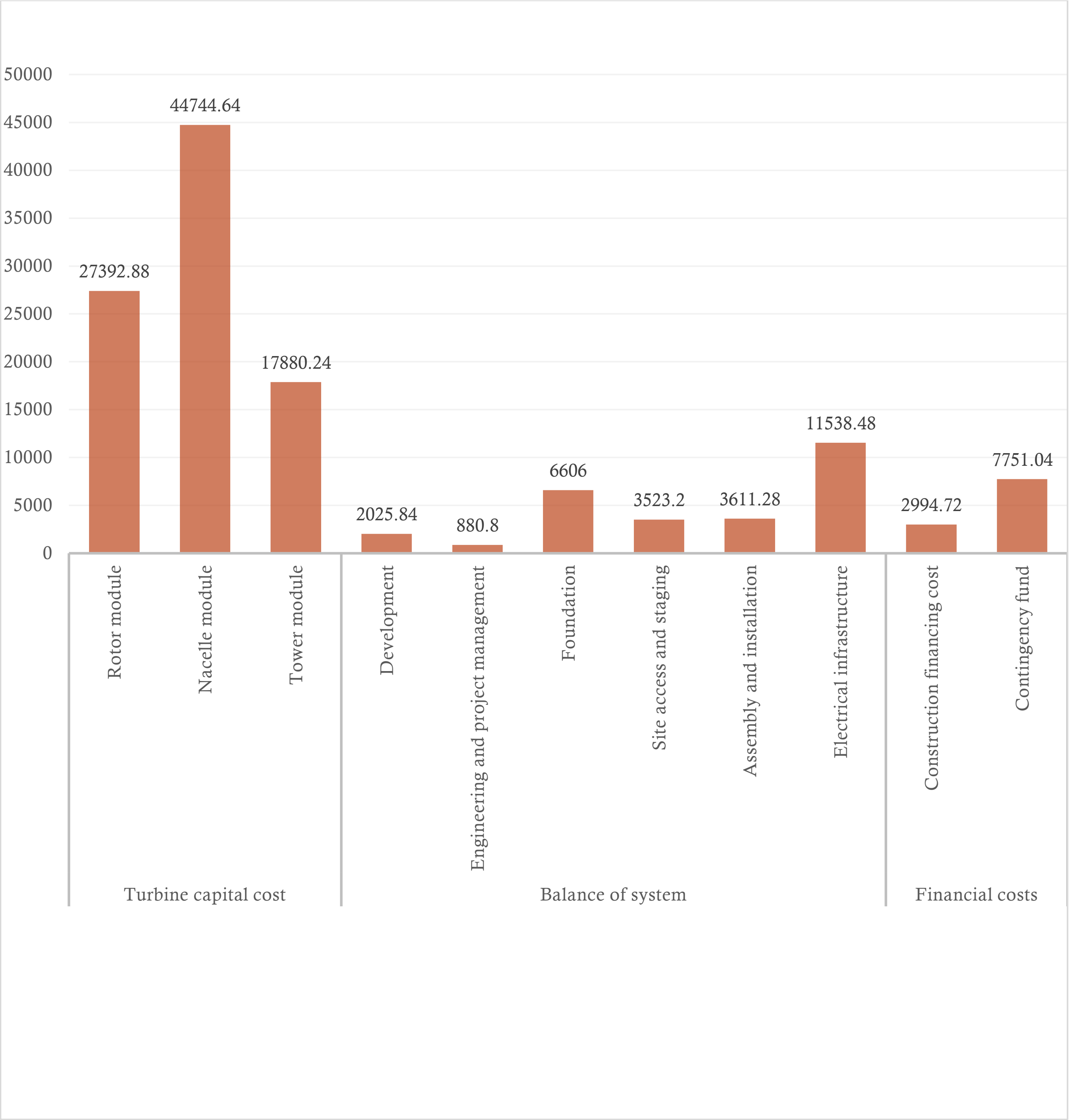

*Figure 4:10: Average cost of installation of onshore wind power plant in USA (in INR/kW)*[56]

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[55] IRENA, "Renewable Power Generation Costs in 2021"

[56] Tyler Stehly and Patrick Duffy, " 2020 Cost of Wind Energy Review". NREL

## 4.4 Integration of V2X with storage systems

The impact of storage on the cost of EV charging is highly dependent on the situation considered. Different parameters such as tariff structure, presence of local RE generations, net metering applicability, interconnection regulations, location, reliability of power, value of lost load (VoLL) etc. play a critical role in determining if the addition of storage to an EV charging station makes economic sense. The potential benefits that can be derived from addition of storage to an EV charging station have been described below.

- **Reduction of high peak prices:** By supplying the energy to the EVs from the stationary storage during peak pricing periods, the CPO can make a substantial amount of cost minimization, the extent of which depends on the tariff structure. The higher the difference between peak and off-peak period energy prices, higher amount of cost minimization is possible.

- **Reduction in demand charges:** Demand charges are levied based on the maximum power drawn by the user (CPO/residential user/others) for the month. So, by controlling the charging of the storage the net power drawn from the grid can be controlled, thereby reducing the total demand charges as shown in Figure 4.11

- **Reduction in connection slabs:** In India the electricity tariff for different groups of customers have been segregated based on their power consumption. For example, in Delhi for non-domestic users up to a rated capacity of 3 kVA are charged INR 6/kVAh, while non-domestic users above 3 kVA are charged at INR 8.5/kVA[57]. So, by optimally controlling the charging/discharging of the storage unit, the connection slab for the customer can be reduced, thereby leading to significant cost savings[58].

- **Local RE firming:** In the presence of local RE generation, the use of battery storage units can be used to fix the net generation profile of the RE plant. This can then be used by the CMS to adequately control the EV charging schedules and reduce the net energy drawn from the grid.

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[57] Data as per DERC Tariff Order for year FY 2021-22.

[58] Adequate regulations and expertise would be necessary here to determine by how much the contracted demand of the user can be altered by with the addition of a storage unit and energy management system.

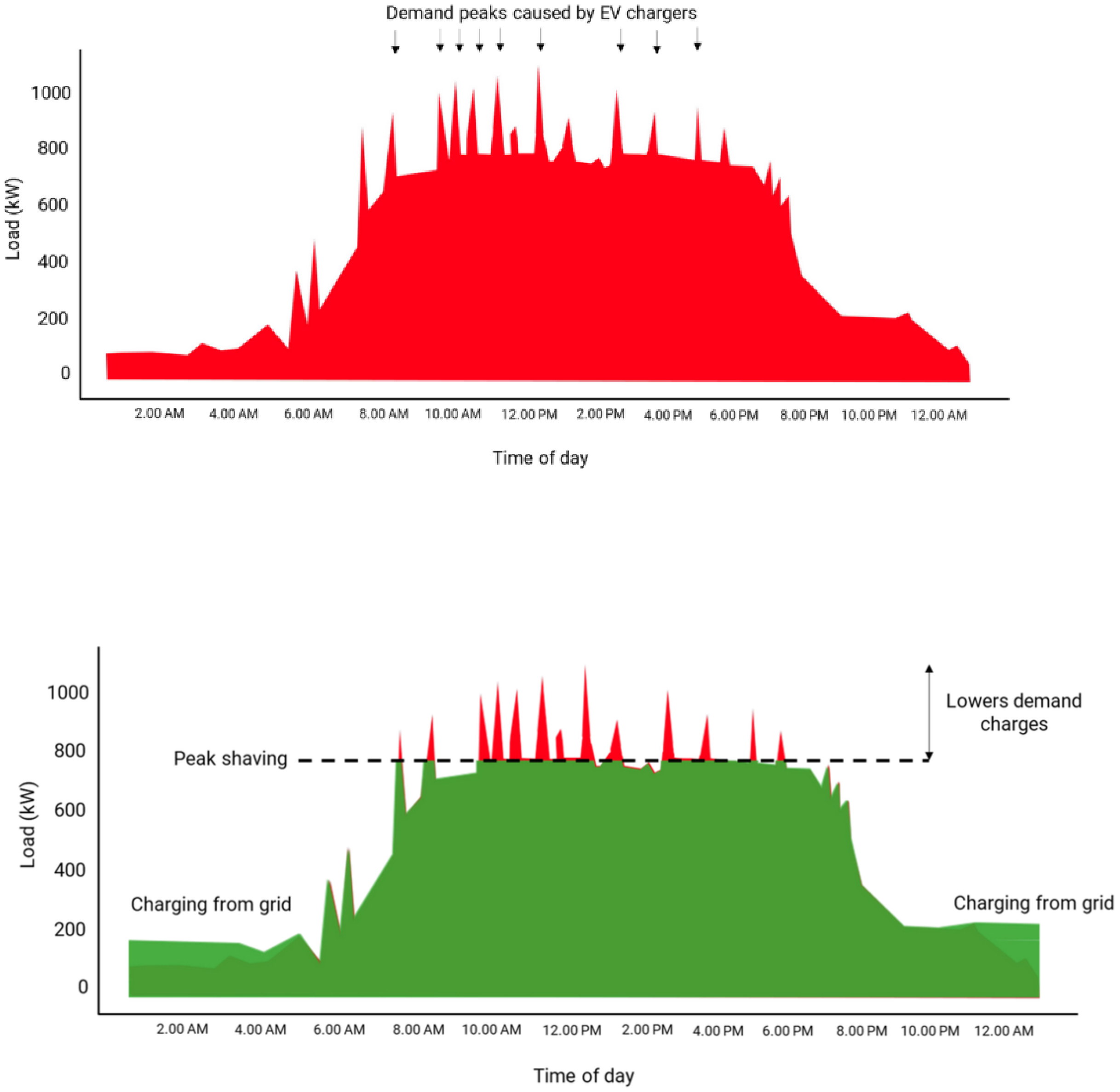

*Figure 4:11: (Up) Demand peaks caused by EV charging leading to higher demand charges and (Down) Using storage for peak shaving resulting in lower demand charges*[59]

- **Accessibility to the energy market:** Another value addition of storage units is that it can potentially include 'EV charging stations with captive storage units' as a participant in the energy markets. In most electricity markets around the world, battery storage units above a certain capacity are allowed to participate in the energy markets. So, by adding a charging station

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[59] EVESCO. "Reduce Demand Charges with Battery Storage". https://www.power-sonic.com/evesco/reduce-demand-charges-with-battery-storage/

alongside an already participating storage unit, can be one of the ways for V2G to access the current electricity markets.

- **Reduction in power losses in the electrical network:** This value addition is more from the perspective of the distribution network operator. By adding a local storage unit near an EV charging station, the power drawn from the grid during peak periods can be reduced, thereby leading to reduction in the power loss in the distribution network.

- **Distribution upgradation can be deferred**: As power for EV charging can be fed locally from the energy storage units, this can also help defer distribution network upgradation requirements bringing much value to the distribution network operators.

# Chapter 5. V2X Enablers

## 5.1 Hardware requirements

### 5.1.1 Unidirectional EV Chargers

As the name suggests, unidirectional EV chargers allow power flow in only one direction. The unidirectional charger primarily consists of an AC to DC converter followed by a DC to DC converter. Usually, a power factor correction circuit is employed between these two converters[60]. A basic block diagram of a unidirectional EV charger is shown in Figure 5:1.

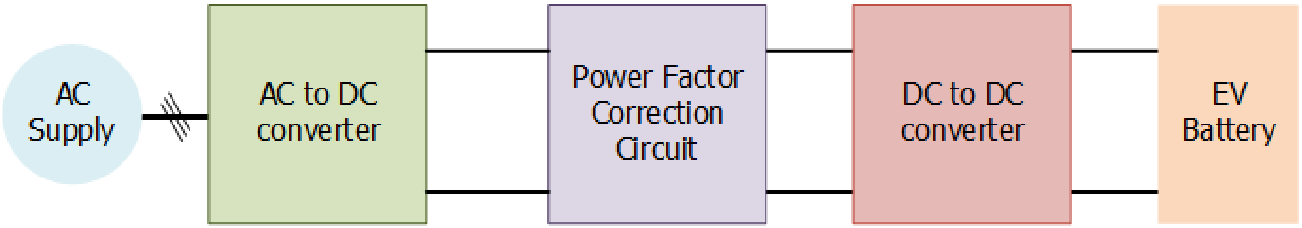

*Figure 5:1. Block diagram of unidirectional EV charger*[60].

The unidirectional AC to DC converter is generally a diode bridge rectifier which is an uncontrolled rectifier circuit. The power factor correction circuit is usually a boost power factor correction circuit which enhances the power factor of rectifier by enhancing the displacement factor of the rectifier. This is usually done to improve the rectifier operation. The output of power factor correction circuit is then fed to the DC to DC converter which the steps up/down the voltage according to EV battery voltage and feed power in EV battery. Some of examples of unidirectional EV charger topologies are shown in Figure 5:2 and Figure 5:3.

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[60] Rangaraju, Jayanth, and Xun Gong. 2020. “Taking Charge of Electric Vehicles-Both in the Vehicle and on the Grid Xun Gong Powertrain Systems Texas Instruments.”

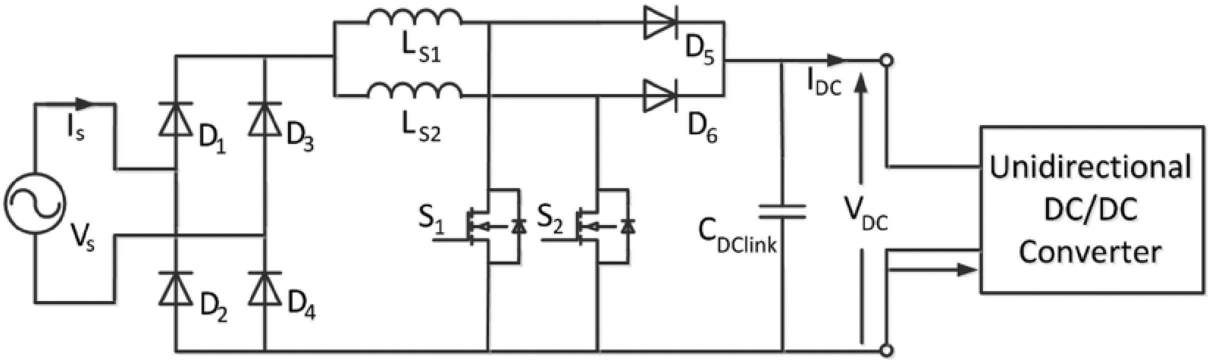

*Figure 5:2. Single-phase unidirectional EV charger with interleaved PFC*[61,62].

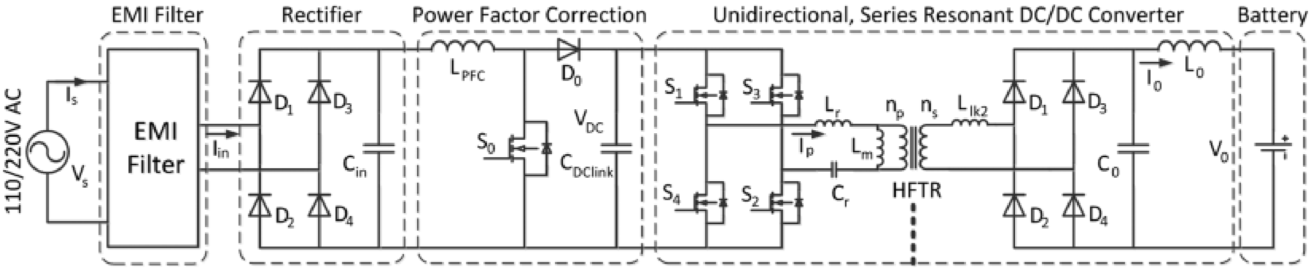

*Figure 5:3. Single-phase unidirectional EV charger with series resonant DC/DC converter*[63,62] .

## 5.1.2 Bidirectional Chargers

Unlike unidirectional EV chargers, bidirectional EV chargers allow power flow in both the directions. The bidirectional charger mainly comprises of bidirectional AC to DC converter followed by a bidirectional DC to DC converter[64]. A bidirectional power factor correction circuit is used between these two converters. A basic block diagram of a bidirectional EV charger is shown in Figure 5:4.

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[61] Musavi, Fariborz, Murray Edington, Wilson Eberle, and William G. Dunford. 2012. "Evaluation and Efficiency Comparison of Front End AC-DC Plug-in Hybrid Charger Topologies." IEEE Transactions on Smart Grid 3 (1): 413–21. https://doi.org/10.1109/TSG.2011.2166413.

[62] Yilmaz, Murat, and Philip T. Krein. 2013. "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-in Electric and Hybrid Vehicles." IEEE Transactions on Power Electronics. https://doi.org/10.1109/TPEL.2012.2212917.

[63] Choe, Gyu Yeong, Jong Soo Kim, Byoung Kuk Lee, Chung Yuen Won, and Tea Won Lee. 2010. "A Bi-Directional Battery Charger for Electric Vehicles Using Photovoltaic PCS Systems." In 2010 IEEE Vehicle Power and Propulsion Conference, VPPC 2010. https://doi.org/10.1109/VPPC.2010.5729223.

[64] Yuan, Jiaqi, Lea Dorn-Gomba, Alan Dorneles Callegaro, John Reimers, and Ali Emadi. 2021. "A Review of Bidirectional On-Board Chargers for Electric Vehicles." IEEE Access. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ACCESS.2021.3069448.

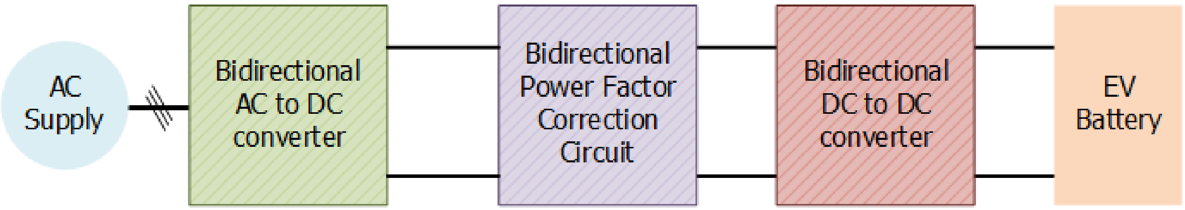

*Figure 5:4. Block diagram of bidirectional EV charger*[64].

The bidirectional AC to DC converter is usually a bridge rectifier which is controlled rectifier circuit consisting of IGBT switches with body diodes. In many bidirectional EV charger topologies, the power factor correction stage is combined with the rectification stage to develop a compact charger topology as presented in [65]. Some of the bidirectional EV charger topologies even omit the power factor correction stage and the power factor of converter is enhanced by modifying the control strategy as presented in[66]. The output of power factor correction circuit is then fed to the bidirectional DC to DC converter which the steps up/down the voltage according to EV battery voltage and feed power in EV battery. Some of examples of bidirectional EV charger topologies are shown in Figure 5:5 and Figure 5:6.

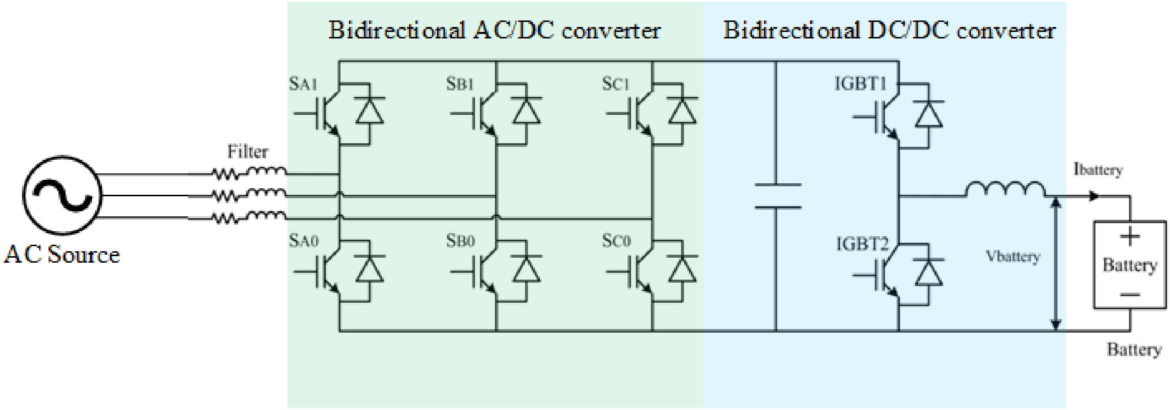

*Figure 5:5. Three-phase bidirectional EV charger*[66].

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[65] Kim, Yun Sung, Gwi Chul Park, Jung Hoon Ahn, and Byoung Kuk Lee. 2016. "Hybrid PFC-Inverter Topology for Bidirectional on Board Charger for Range Extended Electric Vehicle." In 2015 18th International Conference on Electrical Machines and Systems, ICEMS 2015, 521–24. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICEMS.2015.7385090.

[66] Tan, Kang Miao, Vigna K. Ramachandaramurthy, and Jia Ying Yong. 2014. "Bidirectional Battery Charger for Electric Vehicle." In 2014 IEEE Innovative Smart Grid Technologies - Asia, ISGT ASIA 2014, 406–11. IEEE Computer Society. https://doi.org/10.1109/ISGT-Asia.2014.6873826.

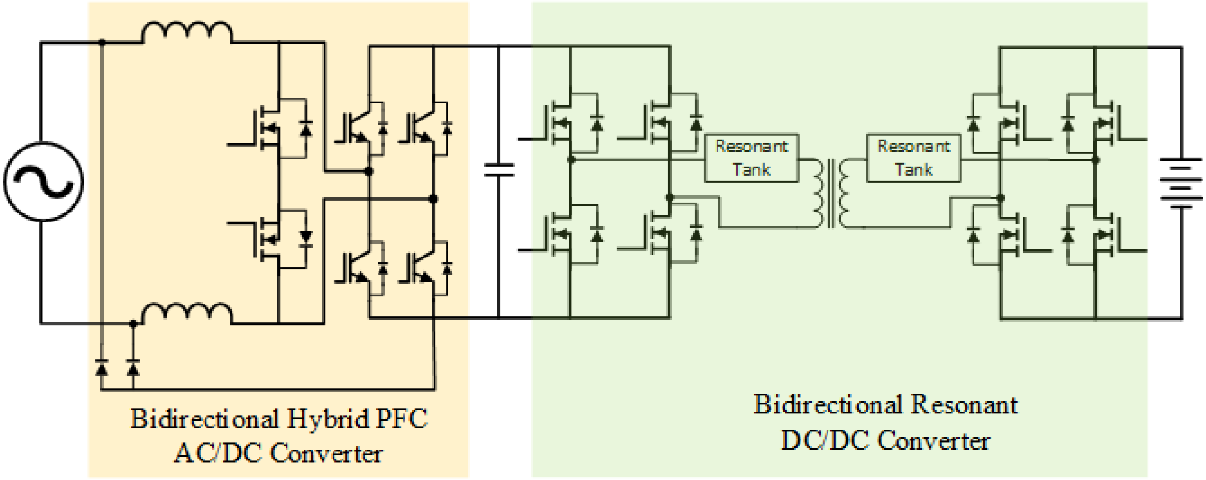

*Figure 5:6. Single-phase EV charger with hybrid PFC AC/DC converter* [65].

There are several topologies of PFC and DC/DC converters as compared in Table 5.1.

*Table 5.1: Comparison of PFC topologies*[67]

| Parameter | 2-Level | 3-Level NPC | 3-Level Vienna | 3-Level TNPC | 3-Level ANPC |
|---|---|---|---|---|---|
| Peak device stress on primary and secondary side | High | Low | Low | Low | Lowest |
| Power density | Low | Higher | High | High | Higher |
| Bidirectional | Yes | Yes | No | Yes | Yes |
| Conduction loss | Low | high | high | Mid | high |
| Switching loss | High | Low | Mid | Mid | Low |
| Efficiency | Low | Very High | High | High | Highest |
| Cost | Low | High | Mid | Mid | High |
| Control | Easy | Mid | Mid | Mid | Mild |

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[67] Ramakrishnan, Harish and Rangaraju, Jayanth, “Power topology considerations for electric vehicle charging stations”, Texas Instruments, 2020.

*Table 5.2: Comparison of DC/DC converter topologies*[67]

| Parameter | LLC Converter | Phase-shifted Full Bridge (PSFB) | Dual Active Bridge (DAB) | DAB in CLLC Mode |
|---|---|---|---|---|
| Peak device stress on primary and secondary side | High | Mild low | Lowest | High |
| Power output to transformer KVA rating | Low | Medium | High | Medium |
| Input and output capacitor RMS currents | High | Medium | Low | High |
| Operation | Unidirectional | Unidirectional | Bidirectional | Bidirectional |
| Total losses | Low | Higher | Medium | Low |
| Control complexity | Moderate | Very simple | Simple to complex | Moderate |
| Paralleling Modules | Intensive | Easy | Easy | Intensive |
| Switching Frequency | Fixed/ High (Si /SiC) | High | High | Very High |

Depending on the location of the converters, V2G hardware can be configured into two different categories as mentioned below,

- **DC V2G:** This is the prevalent V2G hardware currently available in the market. In DC V2G the EVSE houses the entire converter assembly i.e., the bidirectional AC/DC converter, the bidirectional power factor correction circuit and the bidirectional DC/DC converter. The EVSE sends/receives the DC current to/from the BMS in the vehicle to charge/discharge the battery.
- **AC V2G:** Although currently AC V2G is restricted due to interconnection regulations, AC V2G is expected to be much popular than DC V2G as it would much cheaper as compared to DC V2G. In AC V2G, the converter assembly is housed inside the EV itself. So the EVSE just provides AC power to the on-bard charger in the EV. The on-board charger is equipped with a bidirectional capabilities.

### 5.1.3 Bidirectional capabilities of EV

While the potential benefits of bidirectional charging are numerous, the EVs that offer the capability today remain limited. The key difference between V2X and non V2X cars is the battery management system (BMS). The controlling of the current flow to and from the battery, i.e. for both charging and discharging is controlled by the BMS with its main functions being,

- Preventing the charging and discharging of the battery outside of the predefined safety margin.
- The management of power during driving
- Optimizing the charging current and battery temperature to maximize the battery life

In order to facilitate V2X, the BMS should be capable of handling the extra functionalities that arises because of V2X. This may add to the complexity of the BMS. Some of the EVs that currently allow/ expected to have V2X operation are Nissan Leaf, Ford F-150 Lightning, Mitsubishi Outlander PHEV, Volkswagen ID.4[68].

### 5.1.4 Retrofitting of unidirectional EV chargers

A unidirectional EV charger can be converted into a bidirectional EV charger by replacing some components and modifying the control scheme of the charger. The following are the main stages of unidirectional EV chargers that need to be modified to enable bidirectional power flow.

AC/DC converter – The unidirectional EV charger converts AC power into DC power using a diode bridge rectifier. As diodes are unidirectional devices, they do not allow power flow in reverse direction. So, these diodes in bridge rectifier needs to be replaced by controllable switches like IGBTs with body diodes which allows power flow in both the directions as shown in Figure 5:7. An additional control strategy like current and voltage control needs to be developed to control power flow in this converter. The control strategy can be implemented using any common DSP microcontrollers.

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[68] Jones, Peter, "4 Electric cars that can power your house (bi-directional charging)", Motor and Wheels, June 13, 2022. https://motorandwheels.com/electric-power-your-house-bidirectional-charging/

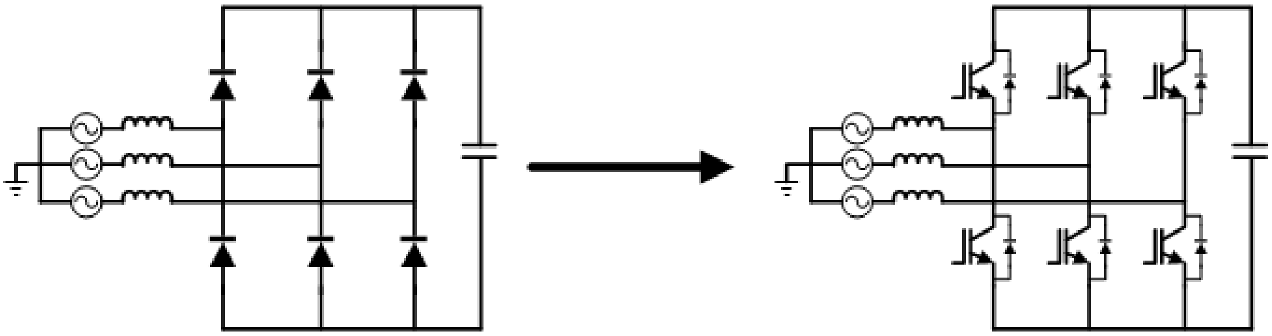

*Figure 5:7. Retrofitting unidirectional AC/DC converter to bidirectional AC/DC converter.*[69]

Power Factor Correction Circuit – This circuit is not mandatory in bidirectional EV chargers as the AC/DC conversion can be controlled in bidirectional EV chargers unlike unidirectional EV chargers that use uncontrolled rectifier like diode bridge rectifier.

DC/DC Converter – The unidirectional DC/DC converters in the unidirectional EV charger needs to be replaced with bidirectional DC/DC converter to enable bidirectional power flow. Most of the EV chargers have buck or boost converters in them. These buck or boost converters can be converted in bidirectional DC/DC chargers by replacing the diode with a controllable switch like MOSFET or IGBT as shown in Figure 5:8. The controller part can be kept same and the inverted (180 degrees phase shifted) pulses can be given to the other switch that has replaced diode. There are many bidirectional DC/DC converter topologies that can be used in bidirectional EV chargers as presented in[70] and[71].

The above discussion tackles the technical layer for retrofitting of unidirectional chargers as V2G chargers. However, there is also the communication layer that would need to be altered, to accommodate the V2X aspects. This can prove to a bit difficult as the details of the communication protocol currently being used in the charger would be required, which the OEMs of the charger may be reluctant to provide. This would then need to be reconfigured based on existing V2X communication protocol (CHAdeMO) or create from scratch which can be a daunting task. Further, there needs to harmonization of the communication protocol of the charger and the communication protocol of the vehicle itself so that the user is able to look at the real time characteristics of the charging and the battery status.

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[69] Review of Bidirectional DC-DC Converter Topologies for Hybrid Energy Storage System of New Energy Vehicles - Jiulong Wang, Bingquan Wang, Lei Zhang, Jianjun Wang, N.I. Shchurov, B.V. Malozyomov

[70] He, Peiwen, and Alireza Khaligh. 2017. "Comprehensive Analyses and Comparison of 1 KW Isolated DC-DC Converters for Bidirectional EV Charging Systems." IEEE Transactions on Transportation Electrification 3 (1): 147–56. https://doi.org/10.1109/TTE.2016.2630927.

[71] Wang, Jiulong, Bingquan Wang, Lei Zhang, Jianjun Wang, N.I. Shchurov, and B.V. Malozyomov. 2022. "Review of Bidirectional DC-DC Converter Topologies for Hybrid Energy Storage System of New Energy Vehicles." Green Energy and Intelligent Transportation, May, 100010. https://doi.org/10.1016/j.geits.2022.100010.

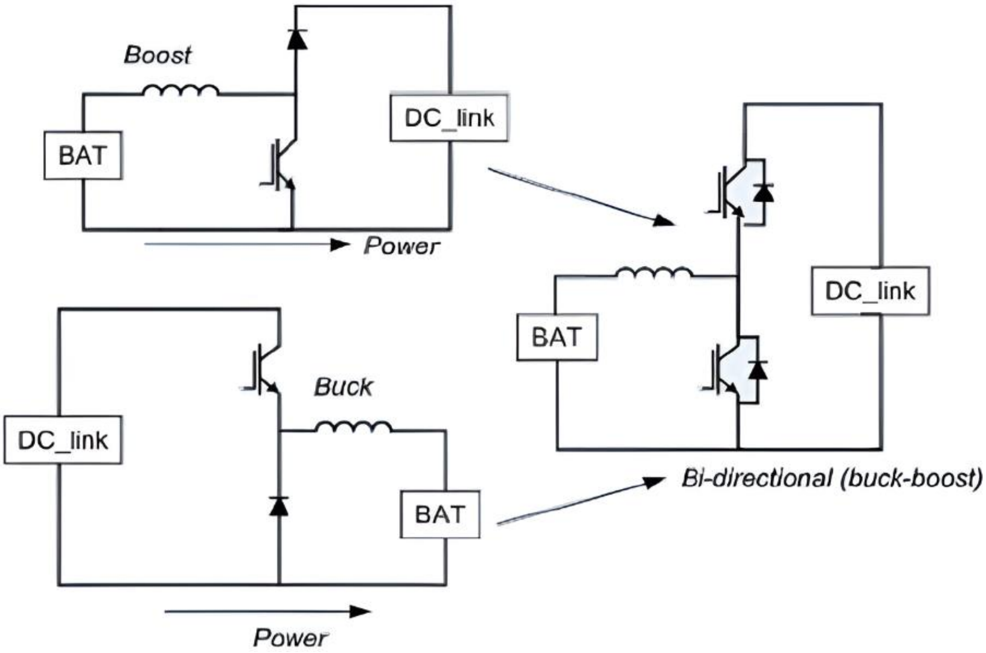

*Figure 5:8. Retrofitting unidirectional DC/Dc converter to bidirectional DC/DC converter.*[68]

So, although retrofitting may be technically theoretically feasible, but international experience[72] has shown that it is difficult, laborious, expensive and would also may nullify the warranty on the EV. Retrofitting was explored for a Toyota Scion (box car) to make it compatible with V2G. Retrofitting was also explored for converting four Citroen C1 EVs to V2G. However, it was observed that the same is technically challenging, complex as well as does not lead to suitable cost economics for the user / OEM. This is because for retrofitting several components need to be replaced in the uni-directional charger leading to appreciable changes in the overall circuit. Making changes in an existing system also renders lesser confidence in the system leading to possible nullification in warranties. Experience from these instances also highlighted that it is difficult to achieve economies of scale in retrofitting.

## 5.2 Communication and data set requirement for different V2X applications

The successful implementation of V2X applications is highly dependent on the communication of accurate, necessary, and reliable data. Depending on the V2X application different sets of data (under different spectrum of use cases such as grid management, authentication etc.) needs to be

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[72] Based on discussion with international experts

communicated among the different stakeholders/entities involved. The details of the data required for each individual V2X application have been highlighted in the subsequent section.

### 5.2.1 V2G

The communication between the different involved stakeholders have been shown in Figure 5.9 and the associated data communicated between the stakeholders are given in Table 5.3

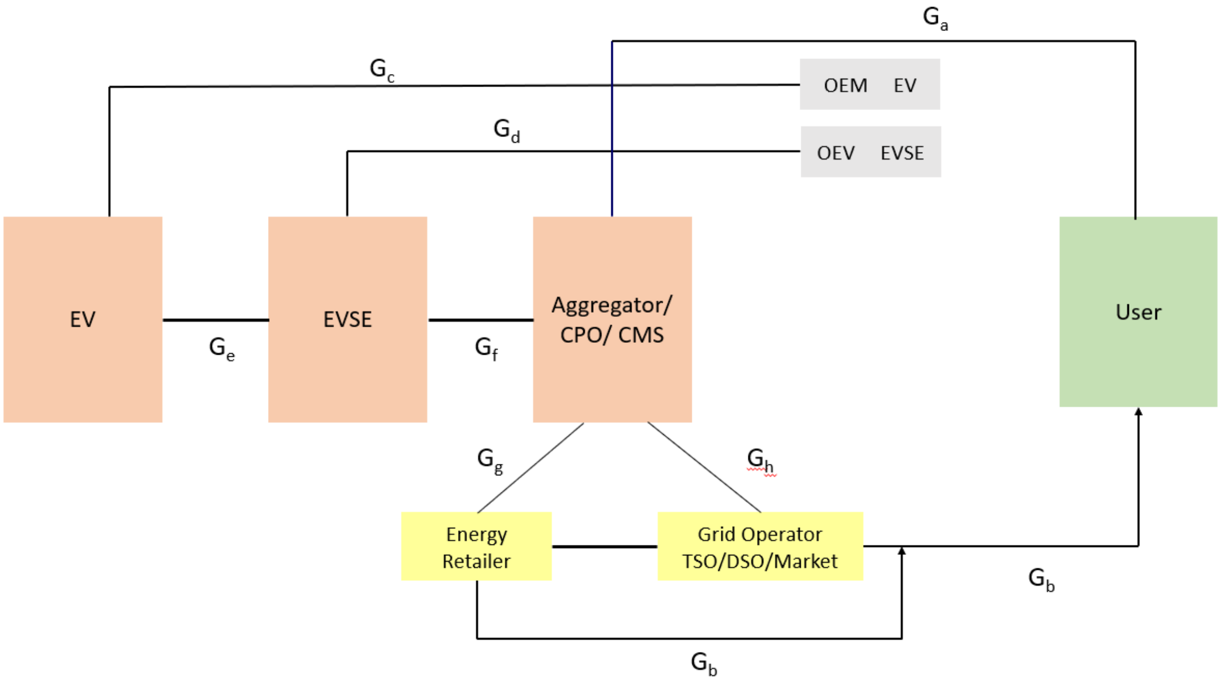

*Figure 5:9: Stakeholders involved in V2G and the communication pathways*

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*Table 5.3: Data set requirement for V2G*

| User and Aggregator | User and Energy Retailer and Grid operator | EV and EV OEM | EVSE and OEM | EV and EVSE | EVSE and Aggregator/CPO /CMS | Aggregator/CPO /CMS and Energy Retailer | Aggregator/CPO /CMS and Operator (TSO/DSO/Market) |
|---|---|---|---|---|---|---|---|
| $G_a$ | $G_b$ | $G_c$ | $G_d$ | $G_e$ | $G_f$ | $G_g$ | $G_h$ |
| Agreement for V2G participation | Energy tariff | Backend support (Troubleshooting) | Backend support (Troubleshooting) | Handshaking and authentication | Handshaking and authentication | Energy tariff (fixed/dynamic) | Connectivity status |
| Expected plug-out time | Demand Response signals for manual response | Product updates | Product updates | Instantaneous battery terminal voltage | User ID | Billing (Active power, Reactive Power consumption) | Active power at PCC |
| Location | | | | Maximum rated charging current | Active Power drawn | Forecasted data(optional) | Scheduled Active Power |
| Added Details about market product | | | | Current SoC | Active power commanded based on response | Time log of energy consumption | Control capabilities (Active power control, reactive power control, power factor control) |
| Energy consumption during charging session | | | | Charging current requirement from EV | Rated capability | Contracted Demand | Voltage measurement at PCC |
| Billing | | | | Target charging current | SoC level | | Active power current measured in PCC |
| | | | | | Battery capacity | | MVAr measured in PCC |
| | | | | | Plug-in time | | PF measured at PCC |
| | | | | | | | Requisite voltage in voltage reference point |
| | | | | | | | System protection |
| | | | | | | | Fault incident recording |
| | | | | | | | Service requirement |
| | | | | | | | Demand response signal |

□ Data required less frequently

### 5.2.2 V2H

The communication between the different involved stakeholders for V2H application have been shown in Figure 5:10and the associated data communicated between the stakeholders are given in Table 5.4.

*Table 5.4: Data set requirement for V2H*

| User and HEMS | User and Energy Retailer | EV and EV OEM | EVSE and OEM | EV and EVSE | EVSE and HEMS/ CMS | HEMS/CMS and Energy Retailer | HEMS/ CMS and Aggregator/ DSO | HEMS/CMS and Local RE/storage | HEMS/CMS and Smart Load |
|---|---|---|---|---|---|---|---|---|---|
| $H_a$ | $H_b$ | $H_c$ | $H_d$ | $H_e$ | $H_f$ | $H_g$ | $H_h$ | $H_i$ | $H_j$ |
| Willing/Unwilling to participate in V2H | Energy tariff | Backend support (Troubleshooting) | Backend support (Troubleshooting) | Handshaking and authentication | Handshaking and authentication | Energy tariff (fixed/dynamic) | Connectivity status | Energy generation (real time) | Rated capacity of individual smart loads, and number of loads |
| Expected plug-out time | Demand Response signals for manual response | Product updates | Product updates | Instantaneous battery terminal voltage | Active Power drawn | Billing (Active power, Reactive Power consumption) | Demand response signal | Rated power and energy capacity of stationary storage | Power drawn (real time) |
| Schedule of other smart loads | | | | Maximum rated charging current | Target active power | Time log of energy consumption | Rated power capability | Current SoC of storage | Target power consumption (real time) |
| Status of connected loads | | | | Current SoC | Rated power capability | Contracted Demand | | Target power drawn/consumed (real time) | |
| Energy consumption during charging session | | | | Charging current requirement from EV | SoC level (instantaneous) | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Billing | | | | Target charging current | Battery capacity (Rated) | | | | |
| | | | | | Plug-in time | | | | |

Low frequency data

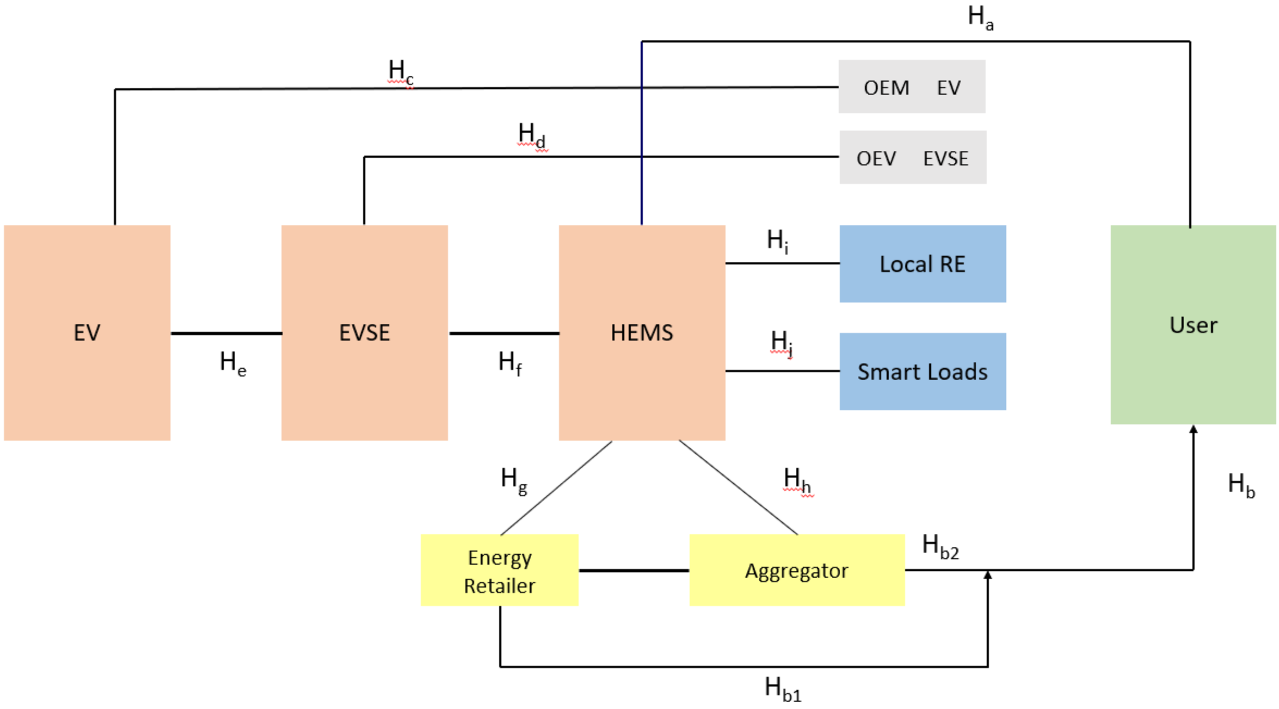

*Figure 5:10: Stakeholders involved in V2H and the communication pathways*

### 5.2.3 V2B

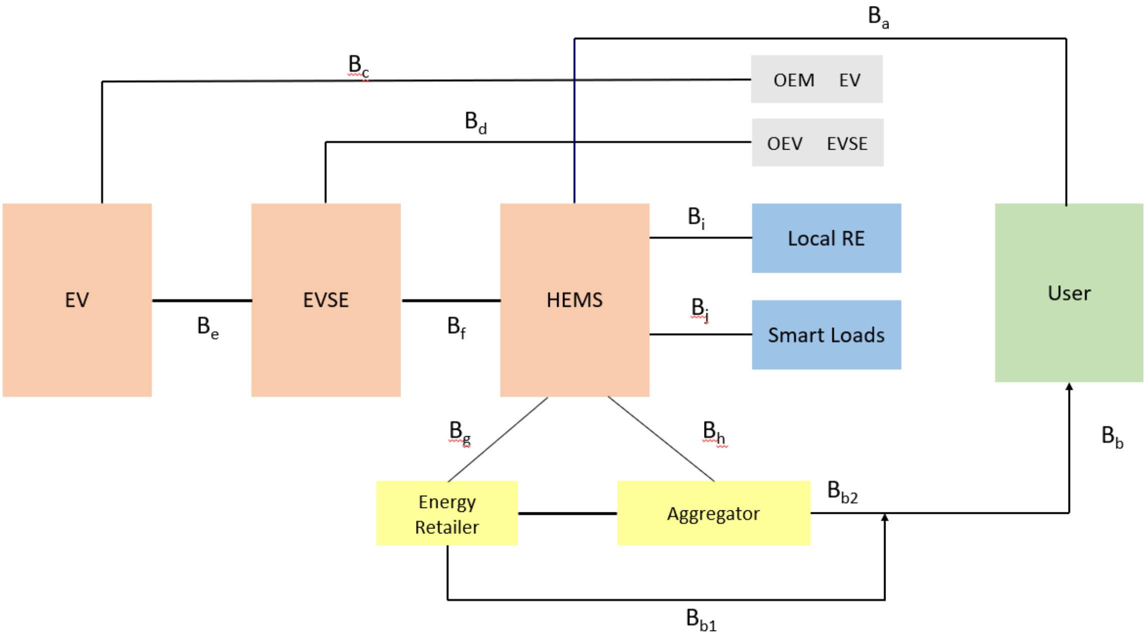

*Figure 5:11: Stakeholders involved in V2B and the communication pathways*

The communication between the different involved stakeholders for V2B application have been shown in Figure 5.11 and the associated data communicated between the stakeholders are given in Table 5.5.

*Table 5.5: Data set requirement for V2B*

| **User and BEMS** | **User and Energy Retailer** | **EV and EV OEM** | **EVSE and OEM** | **EV and EVSE** | **EVSE and BEMS/CMS** | **BEMS/CMS and Energy Retailer** | **BEMS/CMS and Aggregator/ DSO** | **BEMS/CMS and Local RE/storage** | **BEMS/CMS and Smart Load** |
|---|---|---|---|---|---|---|---|---|---|
| **$B_a$** | **$B_b$** | **$B_c$** | **$B_d$** | **$B_e$** | **$B_f$** | **$B_g$** | **$B_h$** | **$B_i$** | **$B_j$** |
| Willing/Unwilling to participate in V2B | Energy tariff | Backend support (Troubleshooting) | Backend support (Troubleshooting) | Handshaking and authentication | Handshaking and authentication | Energy tariff (fixed/dynamic) | Connectivity status | Energy generation (real time) | Rated capacity of individual smart loads, and number of loads |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Expected plug-out time | | Product updates | Product updates | Instantaneous battery terminal voltage | Active Power drawn | Billing (Active power, Reactive Power consumption) | Demand response signal | Rated power and energy capacity of stationary storage | Power drawn (real time) |
| Energy consumption during charging session | | | | Maximum rated charging current | Target active power | Time log of energy consumption | Rated power capability | Current SoC of storage | Target power consumption (real time) |
| Billing | | | | Current SoC | Rated power capability | Contracted Demand | | Target power drawn/consumed (real time) | |
| Requirements of individual users | | | | Charging current requirement from EV | SoC level (instantaneous) | | | | |
| | | | | Target charging current | Battery capacity (Rated) | | | | |
| | | | | | Plug-in time | | | | |

⬜ Low frequency data

## 5.3 Communication Protocol

To facilitate the communication of the data mentioned above there are different communication protocols in place.

### 5.2.4 Communication between EV and EVSE

**IEC 61851** allows for analog communication between the EVSE and the EV. It uses the duty cycle of pulse width modulation (PWM) signal to communicate the different parameters between EV and EVSE. It is the de-facto charging standard in most nations around the globe. However, the analog nature of its communication however limits the functionalities offered by the protocol[73].

**The ISO 15118** standard is a digital signal-based communication protocol. This makes it possible for communication of more complex information between the EVSE and the EV. This communication protocol also enables 'smart charging', which requires the communication of charging capacity, charging time, energy tariffs, battery capacities and the like. It also enables the EVs to be used as distributed storage resources. The communication is based on transmission Control Protocol/Internet Protocol (TCP/IP), Dynamic Host Configuration Protocol (DHCP), and Programmable Logic Controller (PLC). The protocol also allows for V2G applications using the Vehicle-to-Grid transport Protocol (V2GTP) as the communication control layer.

**CHAdeMO** communication protocol which is developed and maintained by CHAdeMO organisation was primarily designed for DC charging. However, CHAdeMO v2.0 the protocol included the possibility of bidirectional transfer of power[74]. As of 2022, the CHAdeMO charging protocol is the only commercially available protocol that enables bidirectional charging.

### 5.2.1 Communication between EVSE and backend (CPO/Aggregator/ CMS/ Energy management system)

**The Open Charge Point Protocol (OCPP)** is used for communication between the EVSE and the CPO. It exchanges the details of the charging event such as the start time of charging, the stop time of charging, energy traded, charging status etc. The core philosophy of OCPP is to provide an open source communication protocol to make any EV charger work with any charging management software even if manufactured by different OEMS. OCPP 1.6 include load balancing as one of its functionalities that allowed CPOs to modulate the charging current for each EVSE[75]. OCPP 2.0.1 also supports bidirectional communication between the CMS and the EVSE which allowed for a more sophisticated smart charging application. It also included support for the ISO/IEC 15118 protocol.

**The Open Smart Charging Protocol (OSCP)** communicates the forecasts of available capacity in the distribution network from the distribution system operator to the CPO. It can be used between

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[73] Zakir Rather, Payal Dahiwale, Dhanuja Lekshmi, Andre Hartung, 'Smart Charging Strategies and Technologies for Electric Vehicles: Simulation based study to evaluate the effects of e mobility smart charging strategies'. GIZ, 2021.

[74] Neaimeh, Myriam, and Peter Bach Andersen. "Mind the gap-open communication protocols for vehicle grid integration." Energy Informatics 3, no. 1 (2020): 1-17.

[75] Zakir Rather, Rangan Banerjee, Angshu Nath, Payal Dahiwale, "Integration of Electric Vehicles Charging Infrastructure with the Distribution Grid: Global Review, India's Gap Analyses and Way Forward - Fundamentals of Electric Vehicle Charging Technology and its Grid Integration", GIZ, 2021

the DSO and the CPO as well as between the CPO and the Home Energy Management System (HEMS) to transmit a 24 hour capacity forecast.

**EEBus** is a protocol suite for communication between consumers, energy producers, smart loads and storage units for energy management primarily for household applications. It is vendor independent and interoperable with different smart home standards such as KNX, Zigbee.

### 5.2.2 Communication between CPO/Aggregator/ CMS/ Energy Management System with DSO/TSO

The **Open Automated Demand Response (OpenADR)** enables smart charging and demand response capabilities in the EV ecosystem. It facilitates open and interoperable demand response solution using pricing signal, capacity availability from DSO, load demand from clients and other relevant information. The protocol is a highly secure, open, smart grid protocol[75]. The standard is also available in version 2.0 and allows the exchange of price signals, setpoints, and metered values between loads, electric storage, distributed generators, and EVs on the one hand, and energy providers and aggregators on the other.

## 5.4 Role of Aggregator

One of the crucial enablers of V2G are aggregators. Their core function is to aggregate multiple EVs and present them as a single entity participating in the different services. They help in managing the risks both on behalf of the grid operators and market players and the and use customers as shown in Figure 5:12. Different aggregator business models are given in Table 5.6

Different stakeholders can play the role of an aggregator depending on their existing business models. Some of the likely stakeholders that can play the role of an aggregator are,

- Energy retailers
- Demand response providers
- Charge point operators
- E-mobility service providers
- Fleet management and vehicle leasing companies
- Vehicle OEMs

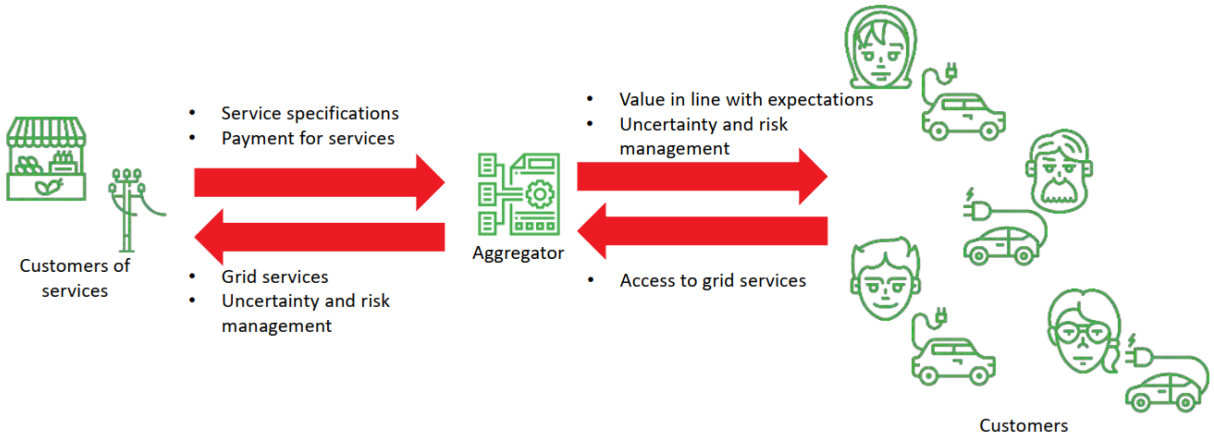

*Figure 5:12: Role of aggregator*[76]

*Table 5.6: Aggregator business models*[76]

| Model | Details | Example |
|---|---|---|
| Combined aggregator - retailer | An energy retailer acts as an aggregator | Octopus Powerloop by Octopus Energy |
| Combined aggregator - market participant | Here the aggregator is an energy market participant but separate to the energy retailer of the customer | JuicePlan by Enel-X |
| Combined aggregator – distribution network operator | The distribution network operator operates as the aggregator. | Electric Nation by Western Power Distribution |
| Independent service provider | Individual aggregator as a service provider for an energy market actor | SwitchDin |
| Customer as aggregator | Large customer acting as an individual aggregator | University of Queensland (Virtual hedging using centralised battery) |

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[76] Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, "The A to Z of V2G: A comprehensive analysis of vehicle-to-grid technology worldwide", Jan 2021

# Chapter 6. Electric vehicles as Virtual Power Plants (VPP)

Virtual power plant is an aggregation of generators and loads coordinated and automated to give rise to a virtual generator that encourages safe, efficient, and cooperative electrical network. It constitutes of an infrastructural layer and a communication layer. Infrastructural layer consist of DERs, loads, storage, dispatchable loads, EV charging stations, and prosumers as in Figure 6:1[77]. The communication layer is responsible for data exchange between different generation and load actors in VPP and executes the major job of coordination and control according to grid conditions as shown in Figure 6:2. The VPP concept enables smaller DER resources and prosumers to indirectly play an active role in grid stability[78,79]. It helps in extracting the maximum benefit from DERs and EVs in the distribution network.

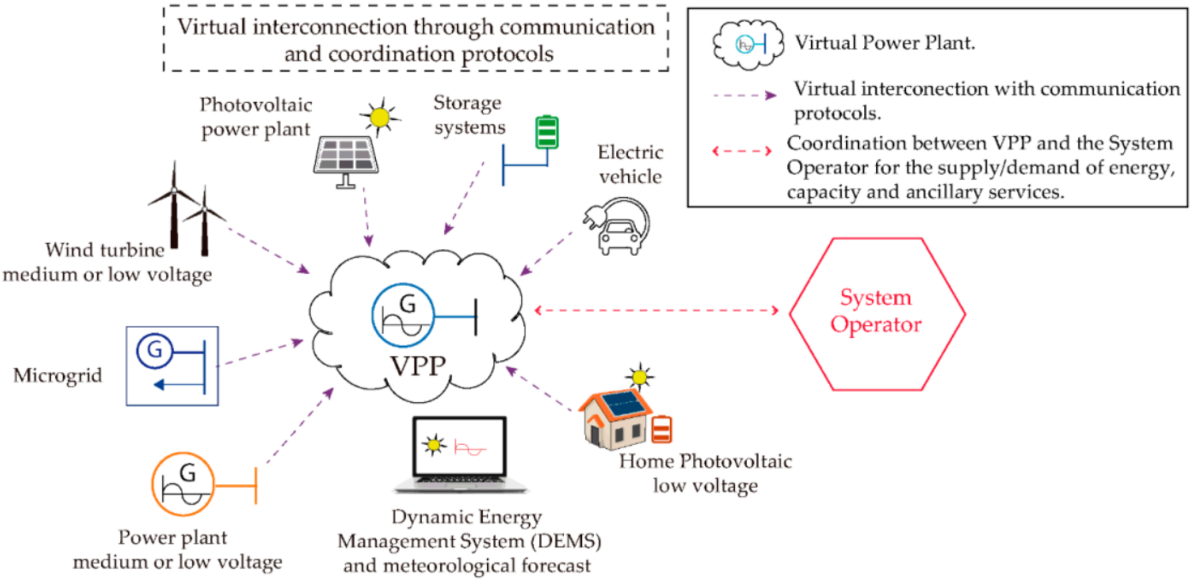

*Figure 6:1. Block diagram of VPP*[80]

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[77] Luo, Fengji, Ali Dorri, Gianluca Ranzi, Junbo Zhao, and Raja Jurdak. "Aggregating buildings as a virtual power plant: Architectural design, supporting technologies, and case studies." *IET Energy Systems Integration* (2021).

[78] Jin, Tae-Hwan, Herie Park, Mo Chung, Ki-Yeol Shin, Aoife Foley, and Liana Cipcigan. "Review of virtual power plant applications for power system management and vehicle-to-grid market development." The Transactions of the Korean Institute of Electrical Engineers 65, no. 12 (2016): 2251-2261.

[79] Pasetti, Marco, Stefano Rinaldi, and Daniele Manerba. "A virtual power plant architecture for the demand-side management of smart prosumers." Applied Sciences 8, no. 3 (2018): 432.

[80] Sarmiento-Vintimilla, Juan C., Esther Torres, Dunixe Marene Larruskain, and María José Pérez-Molina. "Applications, Operational Architectures and Development of Virtual Power Plants as a Strategy to Facilitate the Integration of Distributed Energy Resources." Energies 15, no. 3 (2022): 775.

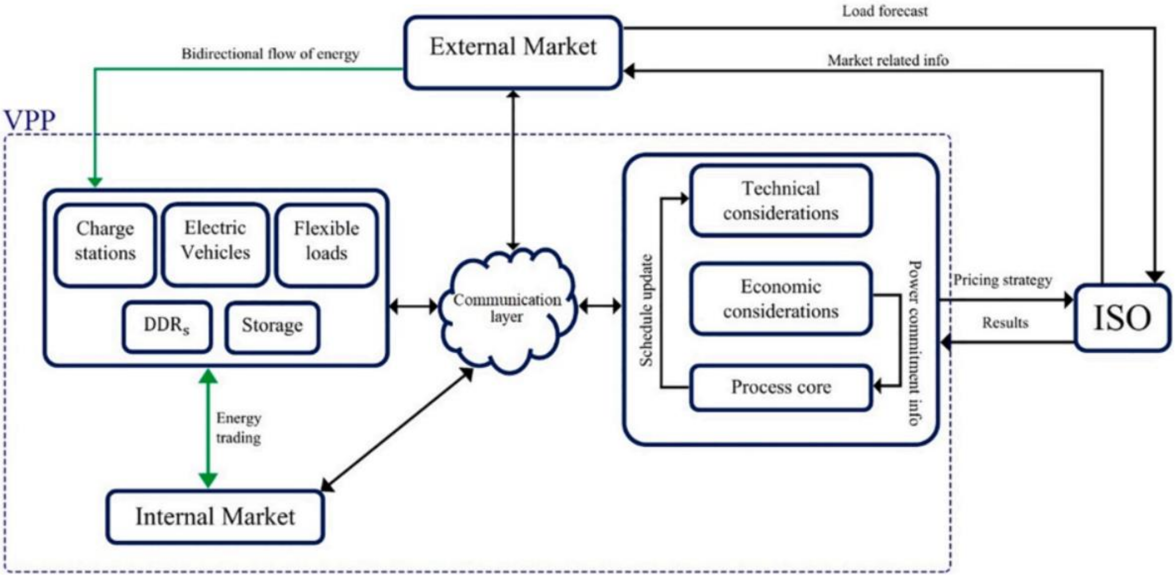

*Figure 6:2. Layout of VPP*[80]

The subsystems of VPP i.e., consumer, prosumer, energy hub, active distribution network (ADN), microgrid (MG), and load aggregator (LA) is shown in Figure 6:3.

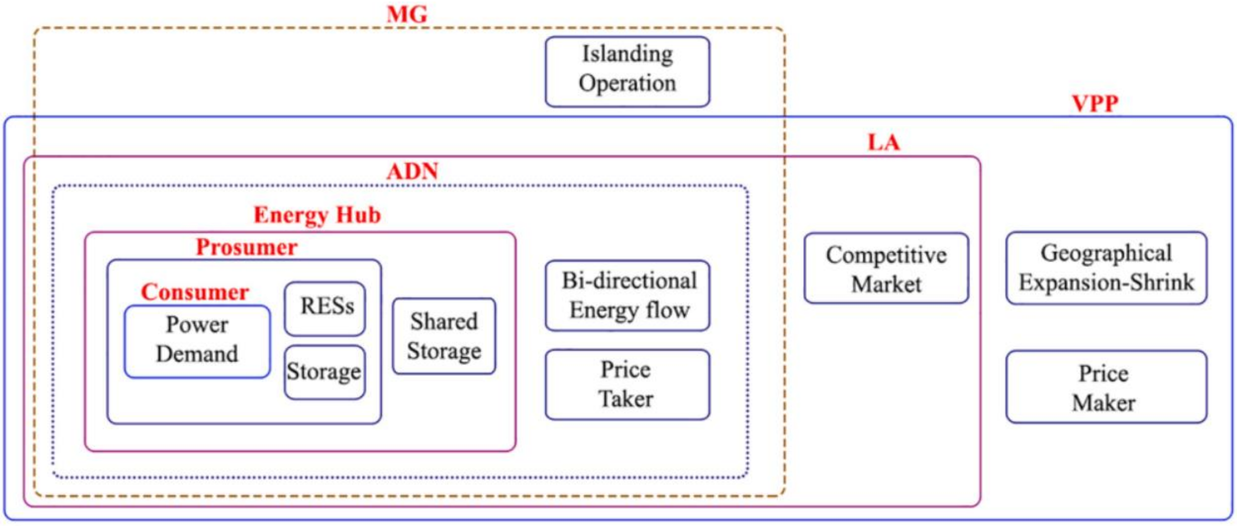

*Figure 6:3. VPP subsystem*[80]

The key characteristics of VPP, given in Figure 6:4 highlights that VPP crosses the bound of geographical locations and focuses on operation, coordination, and market.

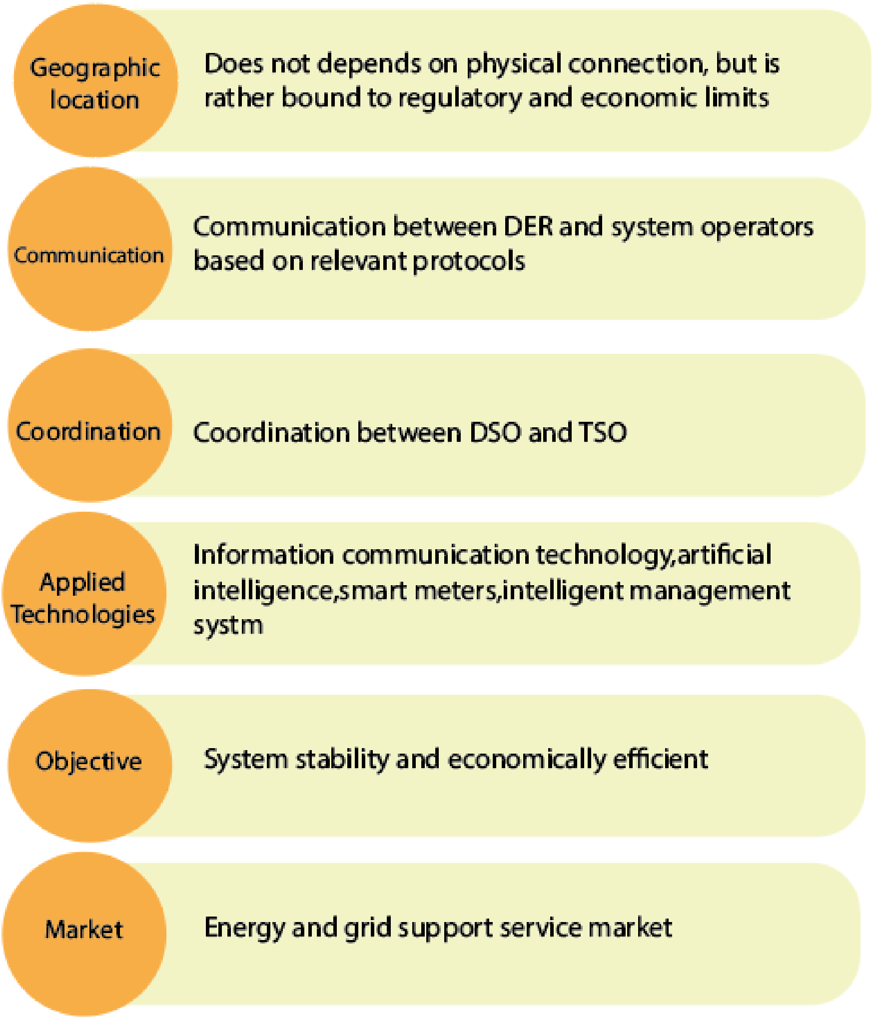

*Figure 6:4. Characteristic of VPP*[80]

Virtual power plant is categorized into commercial VPP (CVPP) and Technical VPP (TVPP) based on scope of objective[81]. In CVPP the focus is on revenue maximization by negotiating the best possible electricity price at electricity market. Opposite to CVPP, TVPP focuses on technical objectives related to system stability. It mainly requires information of power generation by DERs and forecasted power generation and demand to optimally operate the VPP to maintain the stability of the system.

VPP combines various conventional and emerging grids entities as storage, EVs, DERs, flexible load, etc. in coordination to achieve the objective of efficient and stable network. So, VPP adopts bottom-up operational control approach that let easy and efficient access to local

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[81] Mahmud, Khizir, Behram Khan, Jayashri Ravishankar, Abdollah Ahmadi, and Pierluigi Siano. "An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview." Renewable and Sustainable Energy Reviews 127 (2020): 109840.

generation and demand within the VPP[82]. It helps in coordination, control, and bidding process as VPP knows present and forecasted future generation and load information. The comparison of operational architecture of top-bottom and bottom-up approach of conventional grid and VPP is shown in Figure 6:5.

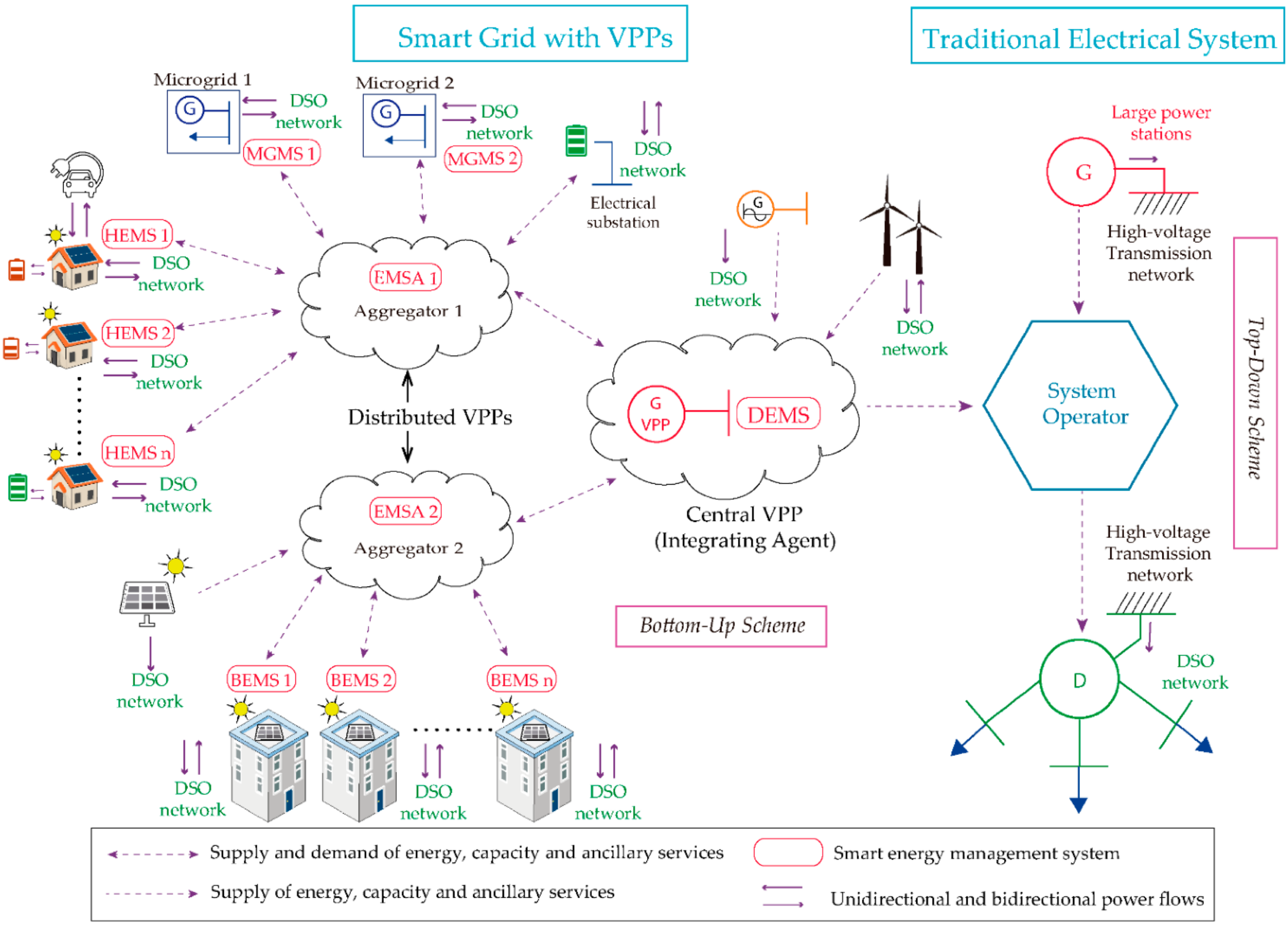

*Figure 6:5. Bottom-up operational approach*[80]

Coordination and scheduling strategy of VPP is broadly divided into five types[83] i.e.,

- Centralized
- Local
- Shared balancing responsibility
- Common TSO-DSO market

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[82] Sarmiento-Vintimilla, Juan C., Esther Torres, Dunixe Marene Larruskain, and María José Pérez-Molina. "Applications, Operational Architectures and Development of Virtual Power Plants as a Strategy to Facilitate the Integration of Distributed Energy Resources." Energies 15, no. 3 (2022): 775.

[83] Mahmud, Khizir, Behram Khan, Jayashri Ravishankar, Abdollah Ahmadi, and Pierluigi Siano. "An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview." Renewable and Sustainable Energy Reviews 127 (2020): 109840.

- Integrated flexibility architecture.

The architecture of centrally controlled VPP as given in Figure 6:6 shows that the VPP directly reacts to the requirement of transmission and distribution network. VPP directly operate for energy offers, reserve power and grid support services by communication with system operator.

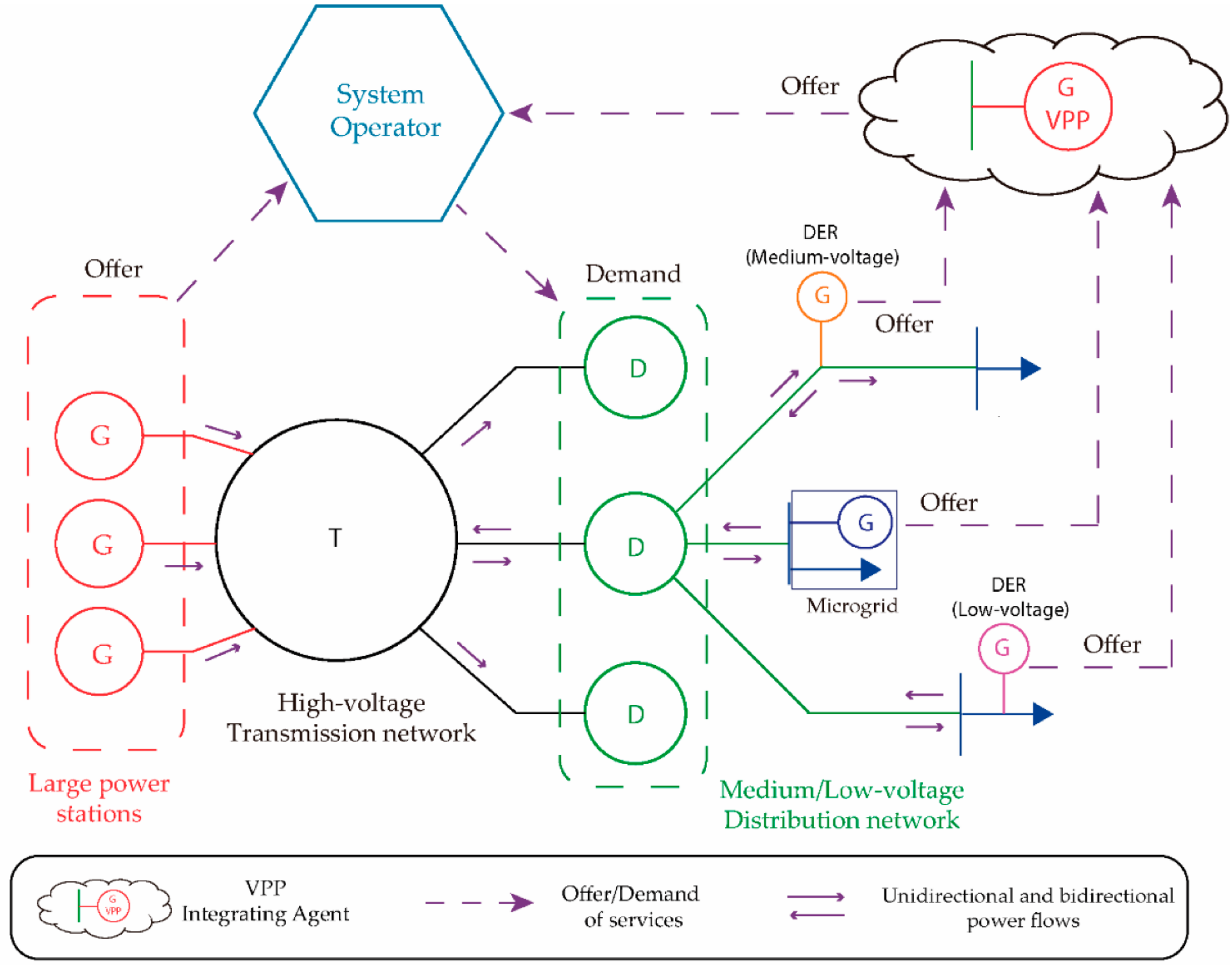

*Figure 6:6. Centralized VPP coordination architecture*[80]

In local coordination architecture in Figure 6:7 , VPP controls the generation and demand within VPP, and coordinates with the DSO instead of the TSO. The DSO then coordinates with the TSO. It implements bottom-up approach for coordination that improves the performance of DER forecast necessary for PP. Once the VPP requirement is fulfilled than the VPP offers bid to DSO and it will bid with system operator.

Shared balancing responsibility model clearly defines the responsibility of system operator and DSO. In this DSO manages local market accomplishing constraints agreed with system operator.

DSO has reserved ability to utilize the flexibility of distribution system while maintaining operation constraints. Common TSO-DSO market model is another coordination model that follows centralized architecture with same technical and economical objective. Another load flexibility model in which the market is headed by independent operator. Considering appropriate coordination scheme, an operation scheduling can be implemented using classical methods, heuristic methods, stochastic optimization, and reinforcement learning method[84].

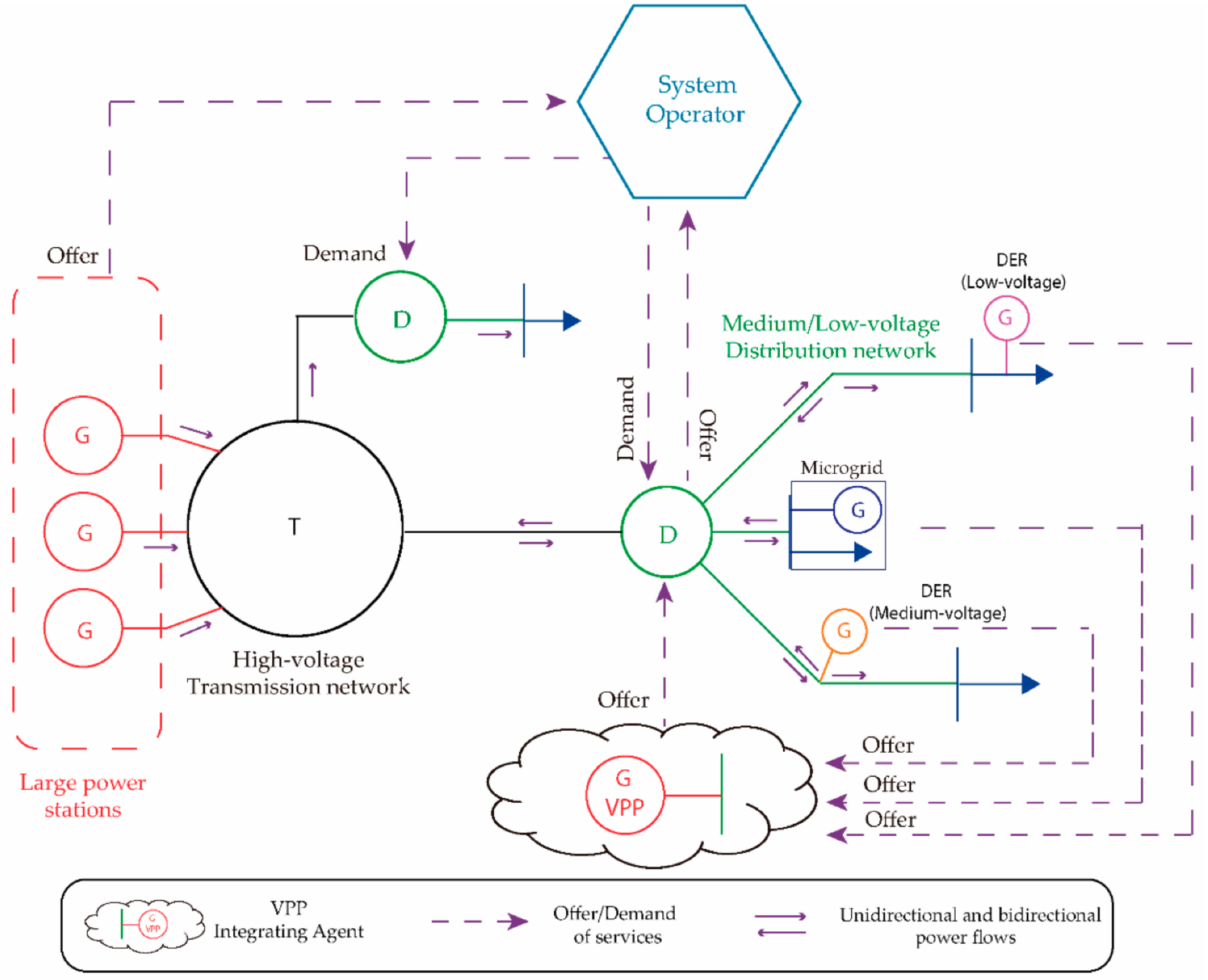

*Figure 6:7. Decentralized VPP[80]*

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[84] Goia, Bianca, Tudor Cioara, and Ionut Anghel. "Virtual Power Plant Optimization in Smart Grids: A Narrative Review." Future Internet 14, no. 5 (2022): 128.

# Chapter 7. Forecasting and scheduling of EV loads

## 7.1 Net load forecasting

Power system attains stability via generation demand balancing. Generation is a dispatchable quantity in the power system and it depends on load demand, which is largely uncontrollable. So, load forecasting is of prime importance to predict the load demand in order to create the generator dispatch schedule of the concerned time period. There are various prediction and forecasting strategies available in the literature for load demand forecasting. With the addition of stochastic elements such as renewable energy generators, DERs, and EVs the conventional load forecasting has shown reduced accuracy. Hence, advanced net load forecasting methods are required in the power system to provide the accurate demand forecasting in presence of DERs and other stochastic resources. Forecasting of electric vehicle demand may need to be separately performed as compared to other loads because of its high characteristic variability in terms of arrival time, departure time, charging power, and charging type.

### 7.1.1 Load Demand forecasting

The effective/net electric load forecasting is the forecast of actual load in presence of renewable generators in the network. The methodology can be broadly classified into deterministic and machine learning based methods[85]. The linear regression based forecasting in [86] uses function-on-function linear regression for a day-ahead forecast that captures a day demand curve. The proposed method converts historical discrete load data into function using cubic B-spline, a piecewise polynomial curve smooth at joints. The historical load data from PJM electricity market is considered in the study and the results were compared with Autoregressive integrated moving average (ARIMA) model. Autoregressive moving average (ARMA) is short term forecasting approach used with the concept of cumulant and bispectrum to facilitate non-gaussian and

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[85] Spyros Tzafestas and Elpida Tzafestas, ‘Computational Intelligence Techniques for Short-Term Electric Load Forecasting’, *Journal of Intelligent and Robotic Systems* 31, no. 1 (1 May 2001): 7–68, https://doi.org/10.1023/A:1012402930055.

[86] Hashir Moheed Kiani and Xiao-Jun Zeng, ‘A Function-on-Function Linear Regression Approach for Short-Term Electric Load Forecasting’, in *2019 IEEE Texas Power and Energy Conference (TPEC)*, 2019, 1–5, https://doi.org/10.1109/TPEC.2019.8662147.

gaussian process [87]. The combined improved method validated higher accuracy for week-ahead and day-ahead forecast on practical system load data provided by Taipower. ARIMA and RNN based method for load forecasting is presented in [88]. ARIMA model learns the nature of past data points via curve fitting. It constitutes of auto regressive part, moving average part, and integrated part. The forecast value of model is expressed as $\hat{X}$, $\hat{X} = \alpha_1 X'_{t-1} + \alpha_2 X'_{t-2} + \ldots + \alpha_p X'_{t-p} + e_t + \theta_1 e_{t-1} + \theta_2 e_{t-2} + \cdots + \theta_q e_{t-q}$, where, $\alpha, \theta$ are coefficients of autoregressive and moving average. $e$ is the error term whereas $p, q$ are the order of autoregressive and moving average model. Auto regressive with exogenous input (ARX) is another model used for forecasting specific loads like cooling load, thermal load, residential and non-residential building loads [89], [90], [91].

### 7.1.1.1 Machine learning based load forecasting:

With increasing availability of data, data driven machine learning based methods viz, artificial neural networks (ANN), recurrent neural networks (RNN), support vector machines (SVM), deep learning (DL), support vector regression (SVR), and long short term memory (LSTM) are being frequently used for net load forecasting. The ANN, SVR, and sky images based combined model is implemented for net load forecasting for solar integrated system [92]. To increase the accuracy of load prediction load curve is decomposed into separate low-frequency and high-frequency load variation signals. The data is then further segregated into day-time and night time data to reduce the effect of variable solar generation on load prediction. The model uses sky images as an exogenous input for daytime load prediction that helps in determining exact value of load. The model is trained for six month load data and results are assessed using mathematical error such as root mean squared error, mean bias error, mean absolute percentage error. Figure 7:1 shows the original load curve and detrended load curve that includes high-frequency violation component of load curve.

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[87] Shyh-Jier Huang and Kuang-Rong Shih, ‘Short-Term Load Forecasting via ARMA Model Identification Including Non-Gaussian Process Considerations’, *IEEE Transactions on Power Systems* 18, no. 2 (May 2003): 673–79, https://doi.org/10.1109/TPWRS.2003.811010.

[88] Rashpinder Kaur Jagait et al., ‘Load Forecasting Under Concept Drift: Online Ensemble Learning With Recurrent Neural Network and ARIMA’, *IEEE Access* 9 (2021): 98992–8, https://doi.org/10.1109/ACCESS.2021.3095420.

[89] Yin Guo et al., ‘Hourly Cooling Load Forecasting Using Time-Indexed ARX Models with Two-Stage Weighted Least Squares Regression’, *Energy Conversion and Management* 80 (1 April 2014): 46–53, https://doi.org/10.1016/j.enconman.2013.12.060.

[90] Riasat Sarwar et al., ‘Field Validation Study of a Time and Temperature Indexed Autoregressive with Exogenous (ARX) Model for Building Thermal Load Prediction’, *Energy* 119 (15 January 2017): 483–96, https://doi.org/10.1016/j.energy.2016.12.083.

[91] Kyungtae Yun et al., ‘Building Hourly Thermal Load Prediction Using an Indexed ARX Model’, *Energy and Buildings* 54 (1 November 2012): 225–33, https://doi.org/10.1016/j.enbuild.2012.08.007.

[92] Yinghao Chu et al., ‘Net Load Forecasts for Solar-Integrated Operational Grid Feeders’, *Solar Energy* 158 (1 December 2017): 236–46, https://doi.org/10.1016/j.solener.2017.09.052.

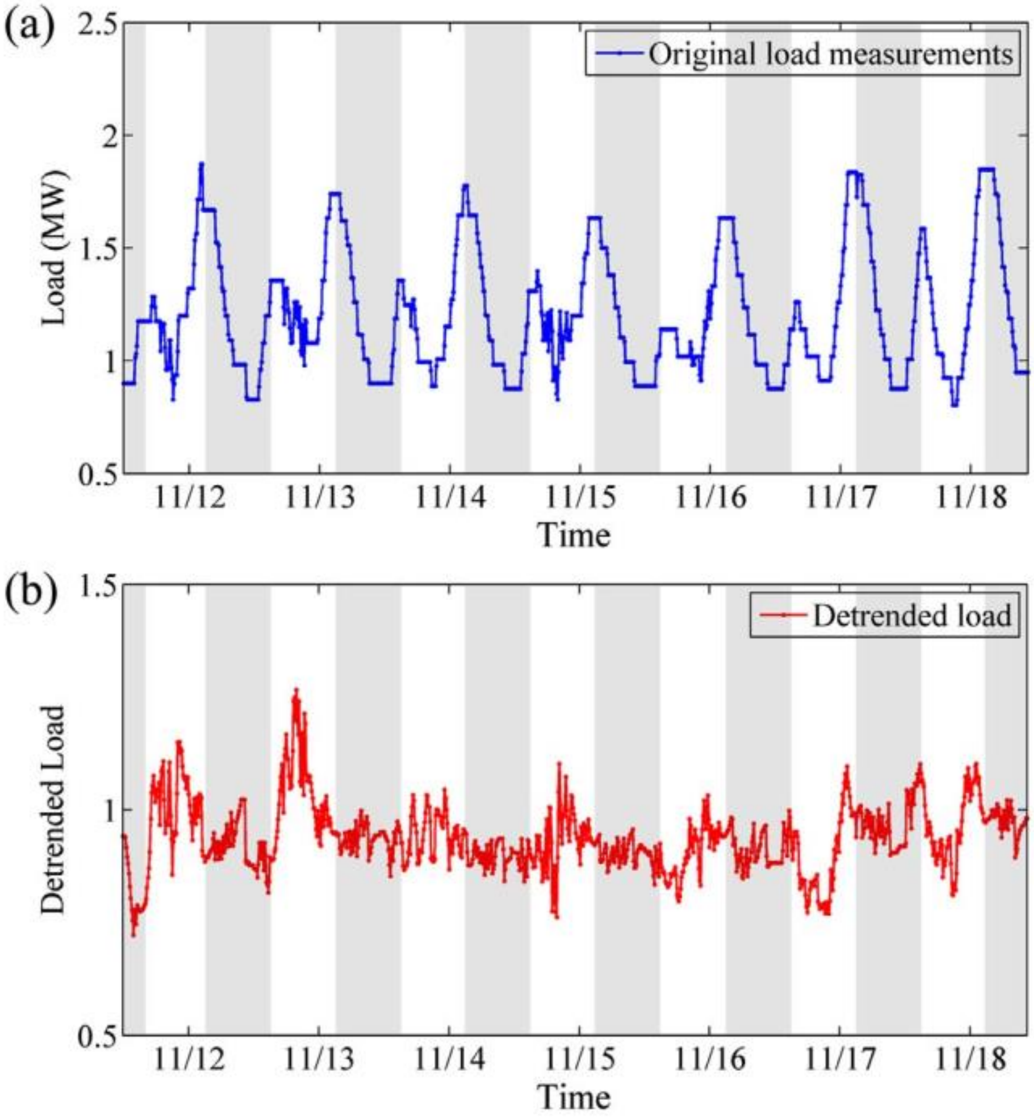

*Figure 7:1 Original and detrended load curve* [93]

Sky images from local hardware as given in Figure 7:2 is used for intra-hour solar forecasting. It assists actual load forecast by using the more accurate value of solar generation.

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[93] Yinghao Chu et al., 'Net Load Forecasts for Solar-Integrated Operational Grid Feeders', *Solar Energy* 158 (1 December 2017): 236–46, https://doi.org/10.1016/j.solener.2017.09.052.

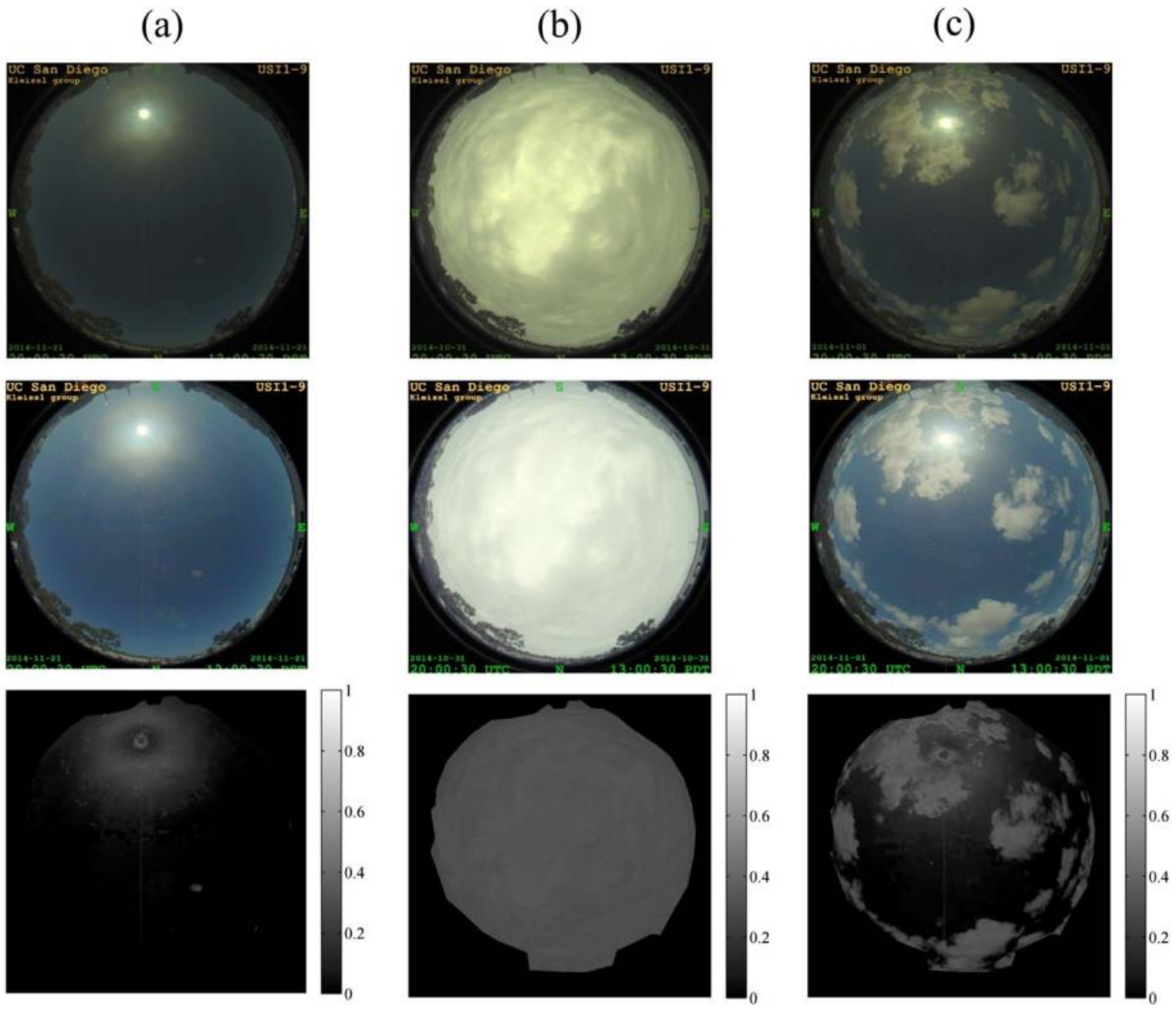
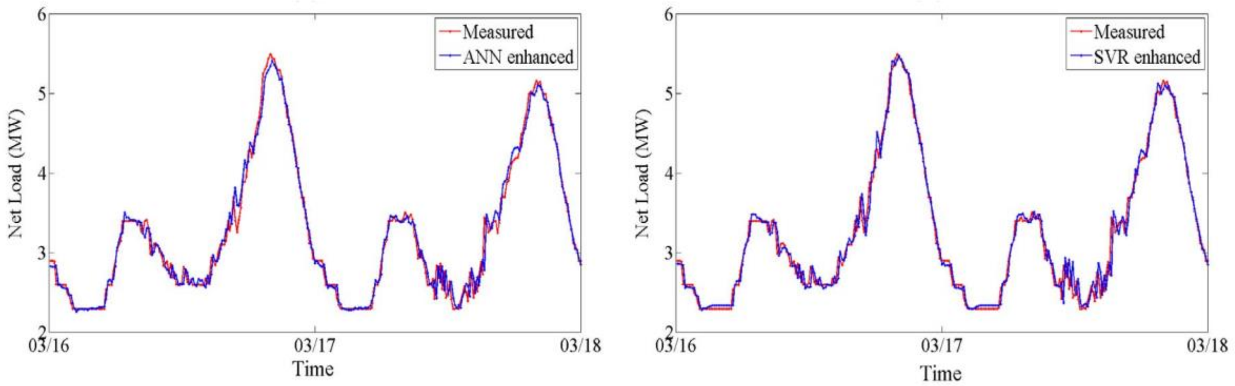


*Figure 7:2 Sky images for weather related parameters information (solar irradiation and clouds)* [94]

10 min, 20 min, and 30 min sampled data based results for ANN and SVR model is shown in Figure 7:3 showing that the higher the time resolution, the better the accuracy of the forecasting..



(a)

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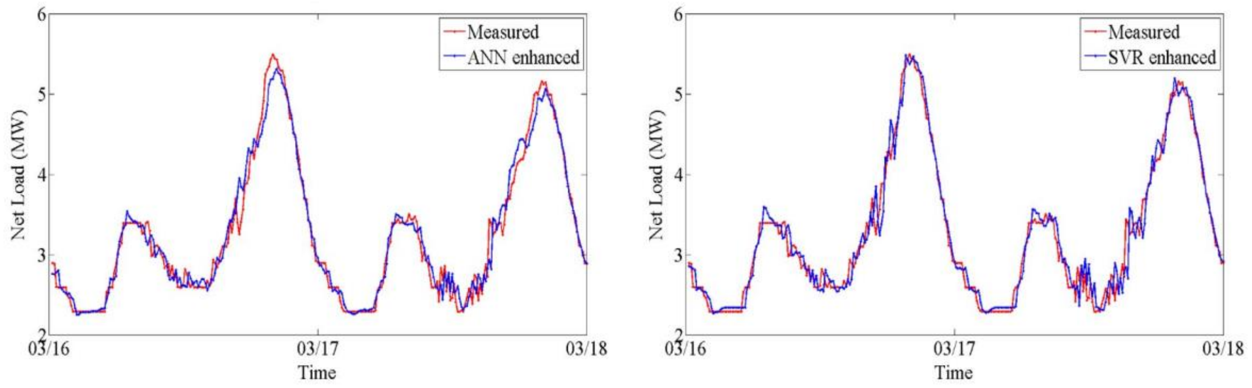
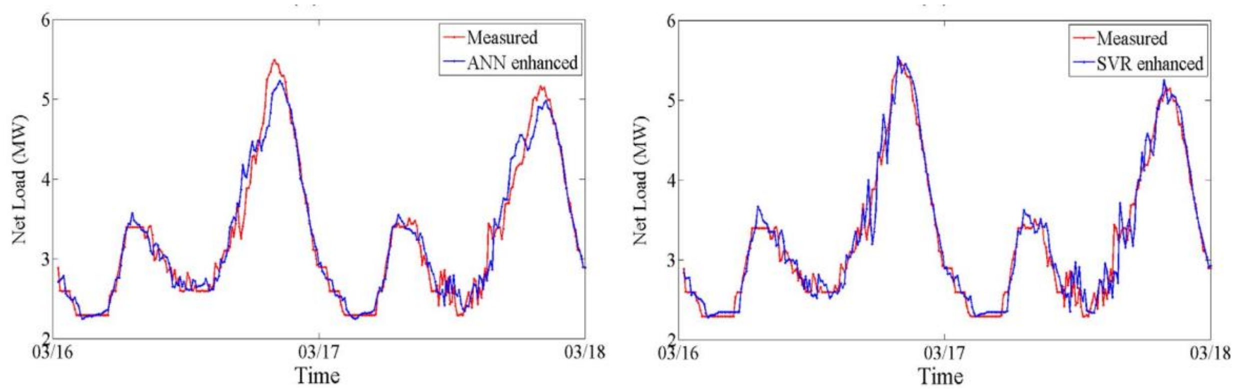
[94] Yinghao Chu et al., 'Net Load Forecasts for Solar-Integrated Operational Grid Feeders', *Solar Energy* 158 (1 December 2017): 236–46, https://doi.org/10.1016/j.solener.2017.09.052.



(b)



(c)

*Figure 7:3. 10 min, 20 min, and 30 min sampled data based results for ANN and SVR model* [95]

Estimation of customer baseline load with PV generation is performed in [96]. It implements a PV-load decoupling framework and then separately estimating the load and PV generations. It applies a machine learning approach to decouple PV power from data. In first step, optimal pairing-based feature extraction is applied on net load curve under different weather conditions. In step two, the extracted features are then provided to a multiple support vector regression model to estimate PV power capacity. The proposed method is tested on Sydney dataset and the results validated the PV power estimation that finally improves the net load forecasting. Ref. [97] works on the similar concept of estimating the PV capacity and forecasting the net load. Maximal information coefficient based correlation analysis and grid search is applied for estimating PV capacity. The net load curve is decoupled into PV capacity, actual load, and residue. Correlation analysis based on copula theory is then used for forecasting the probability of net load characteristic. The study

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[95] Yinghao Chu et al., 'Net Load Forecasts for Solar-Integrated Operational Grid Feeders', *Solar Energy* 158 (1 December 2017): 236–46, https://doi.org/10.1016/j.solener.2017.09.052.

[96] Kangping Li et al., 'Capacity and Output Power Estimation Approach of Individual Behind-the-Meter Distributed Photovoltaic System for Demand Response Baseline Estimation', *Applied Energy* 253 (1 November 2019): 113595, https://doi.org/10.1016/j.apenergy.2019.113595.

[97] Yi Wang et al., 'Data-Driven Probabilistic Net Load Forecasting With High Penetration of Behind-the-Meter PV', *IEEE Transactions on Power Systems* 33, no. 3 (May 2018): 3255–64, https://doi.org/10.1109/TPWRS.2017.2762599.

considers number of month and week, hour of the day, and ambient temperature based regression model to forecast the actual load value. It mentions that if the numerical predication of weather data is not available then ANN, SVM, and gradient boosting regression tress models can be used for forecasting solar irradiation and ambient temperature. The study uses zonal level ISO New England's data of 2013-2014 to validate the proposed method. The results depicts that the method outperforms other forecasting methodologies particularly for higher PV penetrations. The combined deep recurrent neural network and long-short term memory model to exploit the advantages of both methods is used for aggregated load forecasting in solar PV integrated network [98]. To improve the accuracy of the model, uncertainties in residential load and PV generation is considered. It uses Python, Keras API based on TensFlow at the backend. The method is validated over two real world data set and the results are comparably better than multilayer perceptron (MLP) and support vector machine (SVM) model. Spatiotemporal graph (ST graph) dictionary learning optimization is another forecasting technique implemented in [99] using deep recurrent network to find the spatio-temporal features of the net load. The proposed method disaggregates the net load into actual load and PV generation. In this study the unit is represented as spatiotemporal graph (ST graph) where nodes represent net load measurement of the unit and edge reflects mutual correlation between the units. A spatiotemporal autoencoder captures the spatiotemporal manifold of the ST graph. The performance of method on the real-world data in terms of root mean square error, mean absolute error, and mean absolute percentage error for disaggregating and forecasting is presented.

Long-short term memory is a powerful model for features extraction followed by attention based model for forecasting and is used in [100] for short term electric load forecasting It is a data driven model that uses historical data for forecasting. The paper also introduces an early warning system for local sudden large load in enterprises. Enterprise load data is used for validation of proposed forecasting and early warnings system. Ref. [101] introduces a short term load forecasting in presence of concept drift that covers changes in load profile and energy consumption pattern due to additional appliances, change in behavior of customers. It incorporates online learning using RNN while ARIMA model is used in concept drift for its performance. It overcomes the

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[98] Lulu Wen et al., 'Optimal Load Dispatch of Community Microgrid with Deep Learning Based Solar Power and Load Forecasting', *Energy* 171 (15 March 2019): 1053–65, https://doi.org/10.1016/j.energy.2019.01.075.

[99] Mahdi Khodayar et al., 'Spatiotemporal Behind-the-Meter Load and PV Power Forecasting via Deep Graph Dictionary Learning', *IEEE Transactions on Neural Networks and Learning Systems* 32, no. 10 (October 2021): 4713–27, https://doi.org/10.1109/TNNLS.2020.3042434.

[100] Guannan Wang, Pei Yang, and Jiayi Chen, 'Short-Term Electric Load Prediction and Early Warning in Industrial Parks Based on Neural Network', ed. Daqing Gong, *Discrete Dynamics in Nature and Society* 2021 (10 September 2021): 1435334, https://doi.org/10.1155/2021/1435334.

[101] Jagait et al., 'Load Forecasting Under Concept Drift', Online Ensemble Learning With Recurrent Neural Network and ARIMA', *IEEE Access*, vol. 9, pp. 98992–99008, 2021, https://doi: 10.1109/ACCESS.2021.3095420.

limitation of machine learning based load forecasting models in presence of drift that requires re-training. Diebold-Mariano test is implemented to check the difference in the performance of different methods viz, ensemble average, ensemble weighted average, ensemble squared weighted average, ensemble model switching, online adaptive RNN, online linear regression, online bagging regression.

Support vector regression (SVR) is nonlinear regression method used for time series data forecasting application. Historical time series data is used as input for load forecasting in distribution system. The original demand data can contain deviations or errors that leads to inaccurate results of supervised learning algorithms so the pre-processed inputs are considered for training. [102] applied SVR on preprocessed data using grid traversing algorithms and PSO. Preprocessing of real-life demand data results into selection of best parameterized data and then supplied as input to SVR. The study performs 5 minute to 40 minute ahead forecasting whereas results concluded that the 5 minute ahead forecasting has lowest error whereas 40 minute ahead forecasting showed highest inaccuracy. The study also included hour ahead forecasting and the results showed that the method has best performance for short time than hour ahead forecasting.

Considering the dependences of load on the seasonal variations, net load forecasting using seasonal weather information is available in the literature. Load forecasting using seasonal exponential adjustment with regression model is presented in [103] for short term (1-week ahead) load forecasting. In the study, seasonal factor of load curve is verified using Kendall $\tau$ correlation testing method. The seasonal exponential adjustment with regression model is applied for seasonal factor and trend factor respectively. The performance of the proposed method is then examined using paired-sample T test and found that it provides superior load forecast. Random forest (RF) based load forecasting in presence of renewable generators is reported in [104] where, the refined features by rule based methods are used as input for random forest model. This model is validated using Tunisian power company's regular weekdays and weekend's data with average

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[102] Huaiguang Jiang et al., 'A Short-Term and High-Resolution Distribution System Load Forecasting Approach Using Support Vector Regression With Hybrid Parameters Optimization', *IEEE Transactions on Smart Grid* 9, no. 4 (July 2018): 3341–50, https://doi.org/10.1109/TSG.2016.2628061.

[103] Jie Wu et al., 'Short Term Load Forecasting Technique Based on the Seasonal Exponential Adjustment Method and the Regression Model', *Energy Conversion and Management* 70 (1 June 2013): 1–9, https://doi.org/10.1016/j.enconman.2013.02.010.

[104] A. Lahouar and J. Ben Hadj Slama, 'Day-Ahead Load Forecast Using Random Forest and Expert Input Selection', *Energy Conversion and Management* 103 (1 October 2015): 1040–51, https://doi.org/10.1016/j.enconman.2015.07.041.

error of 2.3%. Fuzzy and ANN based combined load forecasting models are also investigated in literature [105, 106].

*Table 7.1: Classification of forecasting methodologies (references for this table are provided at the end of the report)*

| Electrical load forecasting | | EV forecasting | |
|---|---|---|---|
| Deterministic approach | Machine learning approach | Deterministic approach | Machine learning approach |
| Regression[i,ii,iii] | Support vector regression (supervised) [iv,v] | Monte Carlo [vi,vii] (stochastic) | LSTM [viii,ix] |
| Time series approach [x,xi] | Neural Network [xii,xiii] | SARIMAX [xiv] | NN [xv ,xvi] |
| ensemble re-forecast methods [xvii] | Fuzzy neural network [xviii,xix] | SOC based mathematical model [xx,xxi] | SVR [xxii,xxiii] |
| Probabilistic forecasting [xxiv] | Random forest [xxv] | Probabilistic model [xxvi,xxvii] | Ensemble model [xxviii] |
| ARIMA [xxix, xxx] | | | Reinforcement learning [xxxi] |
| ARX [xxxii xxxiii] | | | |

## 7.2 Approaches for EV forecasting

Electric vehicle charging demand is a significant and emerging load that affects the generation-demand balance and load forecasting. EV load forecasting is distinct from traditional load forecasting due to its higher variability in plug-in time, location, duration, and users driving pattern. EVs attains different charging demand profile based on the type and ownership of the EV. So, it is difficult to forecast the demand of EV fleet hence a segregated EV forecasting approach is adopted in literature that separately forecast the EV demand based on ownership such as private vehicle, taxi, bus, and official EV [107]. The probabilistic model is applied for forecasting the EV

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[105] 'Analysis Load Forecasting of Power System Using Fuzzy Logic and Artificial Neural Network | Semantic Scholar', accessed 29 August 2022, https://www.semanticscholar.org/paper/Analysis-Load-Forecasting-of-Power-System-Using-and-Ammar-Sulaiman/8879e6cb8710973f58820f44d781af4142e8f919.

[106] P. K. Dash, A. C. Liew, and S. Rahman, 'Fuzzy Neural Network and Fuzzy Expert System for Load Forecasting', *IEE Proceedings - Generation, Transmission and Distribution* 143, no. 1 (1 January 1996): 106–14, https://doi.org/10.1049/ip-gtd:19960314.

[107] Yanchong Zheng et al., 'A Systematic Methodology for Mid-and-Long Term Electric Vehicle Charging Load Forecasting: The Case Study of Shenzhen, China', *Sustainable Cities and Society* 56 (1 May 2020): 102084, https://doi.org/10.1016/j.scs.2020.102084.

charging profile. The future ownership of the EVs for different types of vehicles are estimated and further used for forecasting the charging profile.

The charging profile of EV varies with mode of charging so different probabilistic model for EV charging profile that considers slow and fast charging modes are investigated for accurate forecasting of demand. A long term EV charging demand forecast using Monte Carlo simulation method is investigated [108]. Forecast modelling of EV ownership adopts different modelling approaches as Bass model and linear regression model. For increasing adoption of private EV technology a Bass model is used for estimating the adoption trend by studying the behavior of investors and buyers and informal publicity. Forecasting the share of taxi, buses, and official vehicle adopts linear regression model due to linear relation in between time and number of vehicles. The survey data of 650 private EVs, 100 electric taxis, 100 electric buses, and 70 official EVs from Shenzhen city in China is used in this study. The estimated ownership of different EV segments are determined for year 2025 using above mentioned estimation models. The results indicated that 880,129 private EVs in high oil price scenario is the expected number of ownership of private EVs in 2025 in Shenzhen. Similarly, 25748 electric taxi, 18263 electric buses, and 6680 official EVs are estimated in 2025. The forecasted EV load profile for weekdays in 2025 for private taxi with scenarios of low and high oil prices are presented in Figure 7:4.

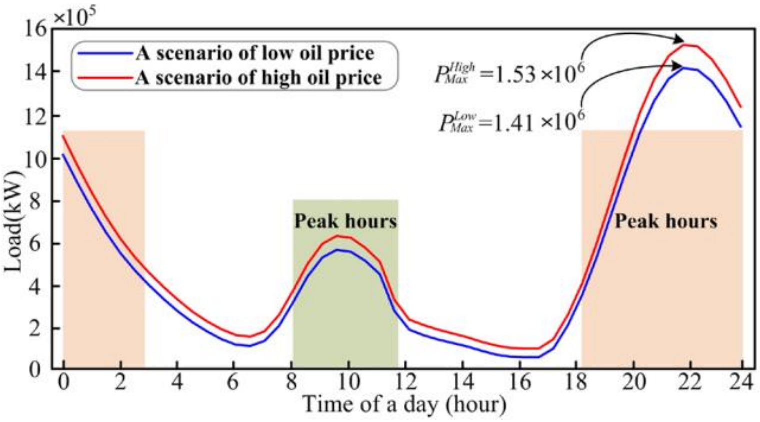

*Figure 7:4 Private EV load prediction for year 2025* [109]

Similarly for taxis, buses, and official vehicles, the weekday predicted charging profile is given in Figure 7:5.

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[108] Zheng et al.

[109] Zheng, Yanchong, Ziyun Shao, Yumeng Zhang, and Linni Jian. ‘A Systematic Methodology for Mid-and-Long Term Electric Vehicle Charging Load Forecasting: The Case Study of Shenzhen, China’. Sustainable Cities and Society 56 (1 May 2020)

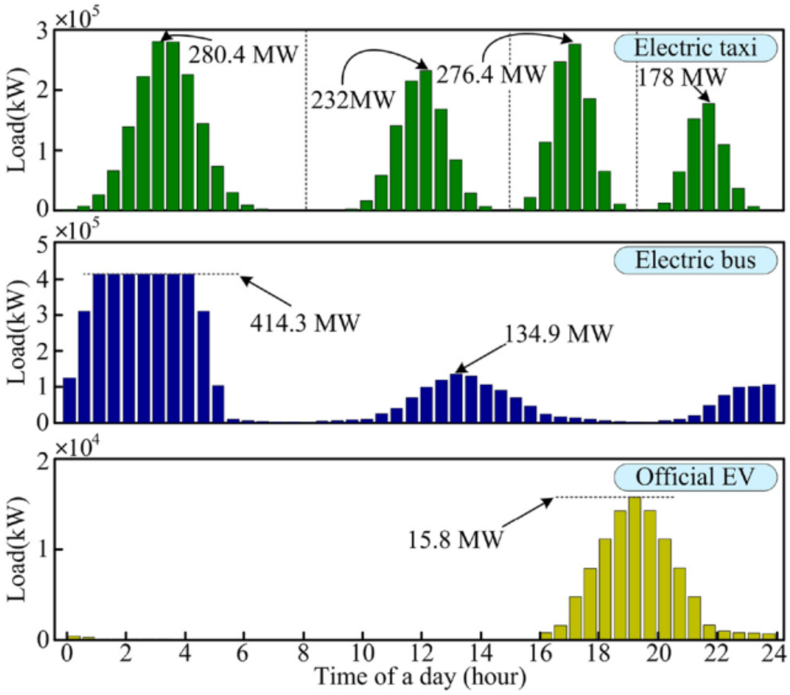

*Figure 7:5 Electric taxi, buses, and official EVs load prediction for year 2025* [110]

The aggregated EV charging demand in 2025 for low and high oil prices are given in Figure 7:6.

The analysis predicted that the peak load would rise by 11.08% in 2025 considering high oil scenario.

### 7.2.1 Machine learning based EV load forecasting:

With increasing data availability and volatile characteristic of EVs data-driven machine learning methods are adopted. Ref. [111] presents a summary of deep learning approaches for EV charging load forecasting. Recurrent neural network model and long short-term memory methods are discussed. LSTM based load forecasting framework is given for two data sets of charging station and office charging site for the period of 2017-2018.

The comparative analysis of ANN, RNN, LSTM, gated recurrent unit (GRU), stacked auto-encoder (SAE), and Bi-LSTM depicts that LSTM has better prediction accuracy for weekdays and holidays. Charging load forecasting using supervisory support vector machine model utilizes historical EV load data, number of EVs, information of charging piles, weather, and day [112].

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[110] Zheng et al.
[111] Zhu et al., ‘Electric Vehicle Charging Load Forecasting’.
[112] Sun et al., ‘Charging Load Forecasting of Electric Vehicle Charging Station Based on Support Vector Regression’.

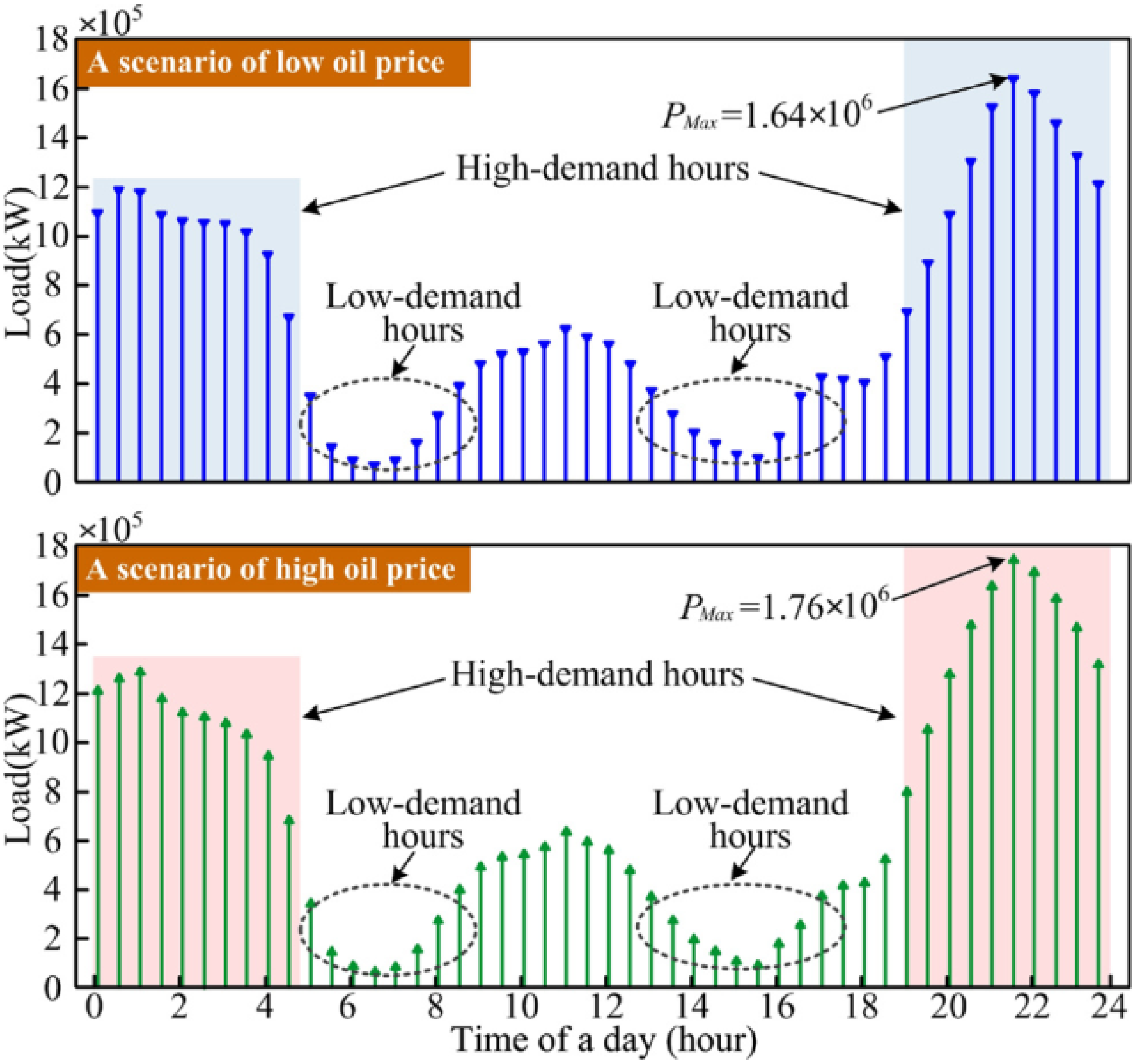

*Figure 7:6 Private electric vehicle load prediction for low and higher oil prices* [113]

The pre-corrected data sample uses average value of previous and next day data sample that improvises the accuracy of the forecast. Stacked auto encoder neural network based load prediction model using key factors as weather, temperature, and historic data is implemented using edge computing platform [114]. Charging load depends on mode/level and type of charging (uncontrolled, controlled) hence, [115] segregate the charge forecasting based on type of charging viz, uncontrolled, controlled, and smart charging. Controlled charging is considered as EV charging at off-peak hours whereas smart charging is taken as centrally controlled charging that

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[113] Yanchong Zheng et al., 'A Systematic Methodology for Mid-and-Long Term Electric Vehicle Charging Load Forecasting: The Case Study of Shenzhen, China', *Sustainable Cities and Society* 56 (1 May 2020): 102084, https://doi.org/10.1016/j.scs.2020.102084.

[114] Anqin Luo et al., 'Load Forecasting of Electric Vehicle Charging Station Based on Edge Computing', in *2020 IEEE 3rd International Conference on Computer and Communication Engineering Technology (CCET)*, 2020, 34–38, https://doi.org/10.1109/CCET50901.2020.9213117.

[115] Morteza Dabbaghjamanesh, Amirhossein Moeini, and Abdollah Kavousi-Fard, 'Reinforcement Learning-Based Load Forecasting of Electric Vehicle Charging Station Using Q-Learning Technique', *IEEE Transactions on Industrial Informatics* 17, no. 6 (June 2021): 4229–37, https://doi.org/10.1109/TII.2020.2990397.

compliance with the interest of utilities and customer. The proposed framework uses ANN and RNN based forecasting as an input to Q-learning reinforcement learning method. Based on the ANN and RNN prediction of previous day, Q-learning decides the best action for EV forecast for 24 hour time horizon. Results shows that the proposed Q-learning method best performs for uncontrolled, controlled, and smart charging compared to ANN and RNN forecasting.

Deterministic time-series based modelling for EV charging load forecasting using autoregressive moving average (ARMA), ARIMA, seasonal autoregressive integration moving average model with external predictor (SARIMAX) are available in literature. EV driving behavior varies with seasonal variations. Owning to the dependency of EV driving pattern on seasons, charging load also varies with seasonal variations. Considering seasonal dependency improved seasonal ARIMA model is investigated and evaluated in [116] for three locations, Washington, Sant Diego, and California. Power consumption data of 2400 charging stations at these locations are considered for two-year time period. Weekday, weekend, near-term, and long-terms forecasting over given data is explored. The data set also incorporate the influence of time-of-use tariff on charging power consumption. EV charging demand is also related to population clusters so, to incorporate this factor used the freely available Portugal census data to estimate spatial EV adoption. Further considering the average value of EV charging power requirement and distance travelled, the multiplication of this quantities will forecast the value of energy required per EV per day.

To combine the advantages of different models combined model with different approaches are investigated. LSTM and Bayesian probabilistic model based combined model is implemented to capture the uncertainty in EV load demand at charging stations [117]. Actual charging station data from Caltech campus is use for implementing the combined model. The proposed model is divided into data-preprocessing unit and forecasting unit whereas data-preprocessing interrelates power consumption data with weather information. The proposed model is compared with multiple linear regression, LSTM, SVR, probabilistic model, and quantile regression. K-nearest neighbour, modified pattern sequence based forecasting, SVR, and RF is investigated in [118]. Ensemble learning model is another combinational model that combines ANN, RNN, and LSTM

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[116] Henry M. Louie, 'Time-Series Modeling of Aggregated Electric Vehicle Charging Station Load', *Electric Power Components and Systems* 45, no. 14 (27 August 2017): 1498–1511, https://doi.org/10.1080/15325008.2017.1336583.

[117] Dan Zhou et al., 'Using Bayesian Deep Learning for Electric Vehicle Charging Station Load Forecasting', *Energies* 15, no. 17 (January 2022): 6195, https://doi.org/10.3390/en15176195.

[118] Majidpour et al., 'Forecasting the EV Charging Load Based on Customer Profile or Station Measurement?'

learner whilst linear regression is applied to learn the weights of base learners [119]. Multiple linear regression model is used for estimating EV adoption.

As forecasting depends on historical non-linear and non-static time series data so, the accuracy of forecast reduces. To improve the accuracy of forecast the original signal is segregated into multiple stationary components and then performs forecasting. Complete ensemble empirical mode decomposition adaptive noise (CEEMDAN) algorithm decomposes signal into residue signal and intrinsic mode functions [120] . Similarly, swarm decomposition decomposes signal into oscillating components using swarm filtering. A bi-level LSTM is supplied with the decomposed signal to achieve more accurate forecast. Results depicts better forecasting performance compared to single decomposition based conventional or hybrid models of MLP, LSTM, and bi-LSTM.

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[119] Xingshuai Huang, Di Wu, and Benoit Boulet, 'Ensemble Learning for Charging Load Forecasting of Electric Vehicle Charging Stations', in *2020 IEEE Electric Power and Energy Conference (EPEC)*, 2020, 1–5, https://doi.org/10.1109/EPEC48502.2020.9319916.

[120] Emrah Dokur, Nuh Erdogan, and Sadik Kucuksari, 'EV Fleet Charging Load Forecasting Based on Multiple Decomposition With CEEMDAN and Swarm Decomposition', *IEEE Access* 10 (2022): 62330–40, https://doi.org/10.1109/ACCESS.2022.3182499.

# Chapter 8. Distribution protection schemes with V2G integration

The current sensing protection devices such as overcurrent relays (OCs), reclosers, and fuses are designed on the assumption of a radial network of the distribution system. With the integration of distributed generators (DGs) and EVs into the distribution network power flow can be bidirectional[121]. Called Vehicle-to-Grid (V2G), EVs can also exchange power with the grid for different grid services.

## 8.1 Classification of Faults

Distribution systems are constantly exposed to fault occurrences due to a variety of factors, including lightning strikes, equipment ageing, human error, and breakdown of power system components. These occurrences have an impact on the reliability of the system, which leads to costly repairs, reduced productivity, and power outages for customers. Fast fault location and isolation are necessary to reduce the impact of fault in distribution systems since fault is unexpected.

A distribution system experiences a fault when it deviates from its intended operational parameters. It could be brought on by a number of things, including direct physical contact between lines that results in a short circuit path, brief interaction with animals or birds, or contact with wind and trees. Some errors only last a short while before they resume their usual functioning. They are referred to as temporary faults. Permanent faults are another kind of fault and they last until the short circuit is located and fixed. If transient problems are not fixed, they will inevitably become permanent faults sooner or later. Permanent faults can occur for a variety of reasons, including incorrect maintenance leading to cable insulation breakdown, things striking overhead power lines, and wires hitting the ground[122].

Distribution systems frequently experience two different fault types: balanced faults and unbalanced faults, sometimes known as symmetrical and asymmetrical faults, respectively. Unbalanced faults make up a large portion of power system issues. Faults can also be classified as

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[121] Telukunta, Vishnuvardhan, Janmejaya Pradhan, Anubha Agrawal, Manohar Singh, and Sankighatta Garudachar Srivani. "Protection challenges under bulk penetration of renewable energy resources in power systems: A review." CSEE journal of power and energy systems 3, no. 4 (2017): 365-379.

[122] Gururajapathy, Sophi Shilpa, Hazlie Mokhlis, and Hazlee Azil Illias. "Fault location and detection techniques in power distribution systems with distributed generation: A review." Renewable and sustainable energy reviews 74 (2017): 949-958.

shunt faults and series faults[123]. Unbalanced series impedance on a line results in a series fault. It stands represents an open conductor. A series fault happens when there is a broken line in one or more lines in a power system network. Frequency, voltage rise, and current drop at the faulty phases are used to categorize series faults.

Shunt fault is typically experienced in distribution systems. For locating and isolating the faulty circuit in a distribution system, phase-overcurrent relays and ground-overcurrent relays are frequently utilized. Shunt faults are characterized by an increase in current and a decrease in voltage and frequency. Shunt faults on a three-phase line can be -

- Single line to ground faults (SLGF)
- Double line to ground faults (DLGF)
- Line to line faults (LLF)
- Three-phase to ground faults (LLLGF)[124]
- Single conductor open fault
- Two conductor open fault

## 8.2 Protection coordination challenges

The nature of fault currents arising due to increased integration of distributed generation (DG) and EVs may be intermittent and may introduce significant challenges to the existing protection schemes[121]. The conventional protection strategies may fail to intercept the faults in the presence of these distributed resources due to different conditions. So, these conventional protection schemes would need modifications to cater to the issues. Some of the major protection issues that need to be addressed for an effective distribution network protection are described in this section.

### 8.2.1 Change in fault current Level

The conventional protection schemes operate on the basis of the severity of fault current value, duration of the fault, and network configuration. Due to the presence of inverter-interfaced DG, renewable energy sources (RES) DGs and even V2G resources operating in islanded mode or grid connected mode with each injecting different fault current into the grid, it becomes challenging for the protection system to distinguish between actual fault and temporary faults or transients[125].

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[123] Turan Gönen. Electrical Power Transmission System Engineering. Apple Academic Press, 2014

[124] Lim, Philip K., and Douglas S. Dorr. "Understanding and resolving voltage sag related problems for sensitive industrial customers." In 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 00CH37077), vol. 4, pp. 2886-2890. IEEE, 2000.

[125] Najy, Waleed KA, Hatem H. Zeineldin, and Wei Lee Woon. "Optimal protection coordination for microgrids with grid-connected and islanded capability." IEEE Transactions on industrial electronics 60, no. 4 (2012): 1668-1677.

The fault current contributed by the high penetrated synchronous DGs is 5 to 6 times its nominal current rating[126] which leads to significant variations in the fault current. On the other hand, inverter interfaced DGs and V2G units limits their maximum output fault current to 1.1 to 3 times its nominal rating[127]. This is due to the low thermal overload capacity of power electronic switches used in them.

### 8.2.2 Protection Blinding

The introduction of large number of V2G units in the network results in the flow of bidirectional power in the feeders, which would introduce different protection issues, such as new fault current sources, and the reduction of the reach of relays. The impact of these V2G units on the protection scheme also depends on the location and size of the V2G units. Considering the network shown in Figure 8:1, where a V2G unit is connected to Bus 1, and a fault occurs near Bus 2. The current division at bus 1 changes the equivalent Thevenin impedance as seen by upstream relay R1. The relay R1 senses lesser due to the current injected by the V2G unit at Bus 2, hence it underreaches the fault. This undesirable effect is known as protection blinding[128].

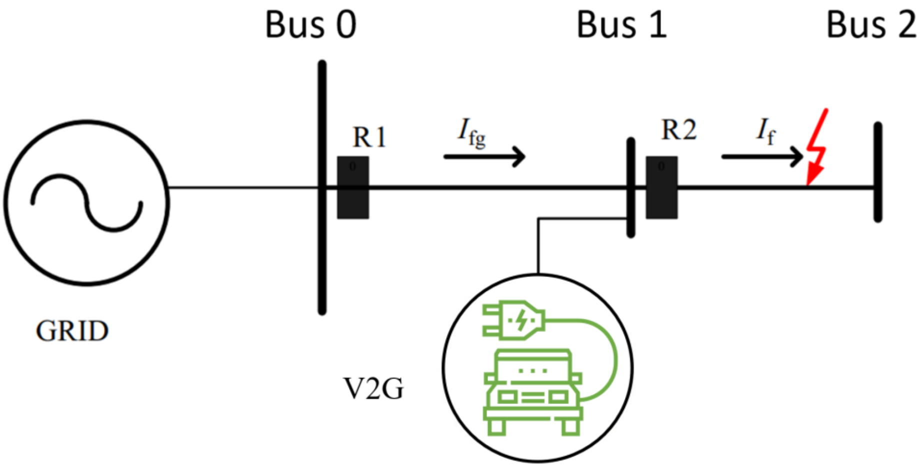

*Figure 8:1: Protection blinding effect due to V2G*

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[126] Margossian, Harag, Juergen Sachau, and Geert Deconinck. "Short circuit calculation in networks with a high share of inverter based distributed generation." In 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), pp. 1-5. IEEE, 2014.
[127] Keller, James, and B. Kroposki. Understanding fault characteristics of inverter-based distributed energy resources. No. NREL/TP-550-46698. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2010.
[128] Hussain, B., S. M. Sharkh, S. Hussain, and M. A. Abusara. "Integration of distributed generation into the grid: Protection challenges and solutions." In 10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change, pp. 1-5. IET, 2010.

### 8.2.3 Sympathetic Tripping

Sympathetic tripping occurs when a healthy feeder gets tripped due to fault in an adjacent feeder. This primarily happens due to injection of bidirectional current. As shown in Figure 8:2, if a fault occurs at an adjacent bus, then a significant portion of fault current may be fed by the DGs or V2G units. This leads to increase in the relay pickup current connected at the healthy feeder and consequently results in tripping of relay R2 rather than the faulted feeder relay R1.

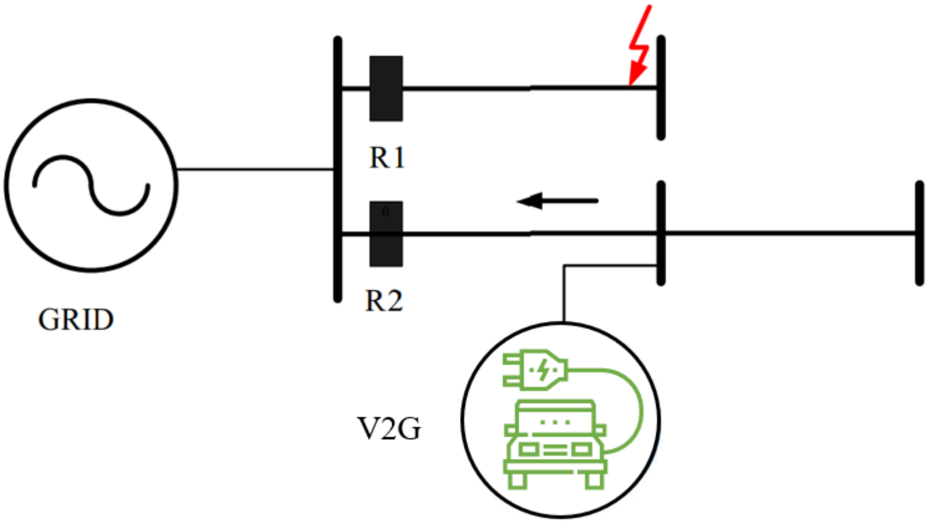

*Figure 8:2: Sympathetic tripping due to V2G*

### 8.2.4 Unintentional islanding

Another important consideration to maintain power system reliability in unintentional islanding. As shown in Figure 8:3, if relay R2 is activated due to fault current, then it will lead to islanded operation of the RES. If the DGs/V2G units connected to the micro grid continue to supply power to the grid during Loss of Mains event, it can lead to power imbalance, voltage and frequency issues to the network. So, it is desirable that relevant protection schemes get activated to avoid undesirable operations in microgrid during islanded mode[129].

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[129] Blaabjerg, Frede, Yongheng Yang, Dongsheng Yang, and Xiongfei Wang. "Distributed power-generation systems and protection." Proceedings of the IEEE 105, no. 7 (2017): 1311-1331.

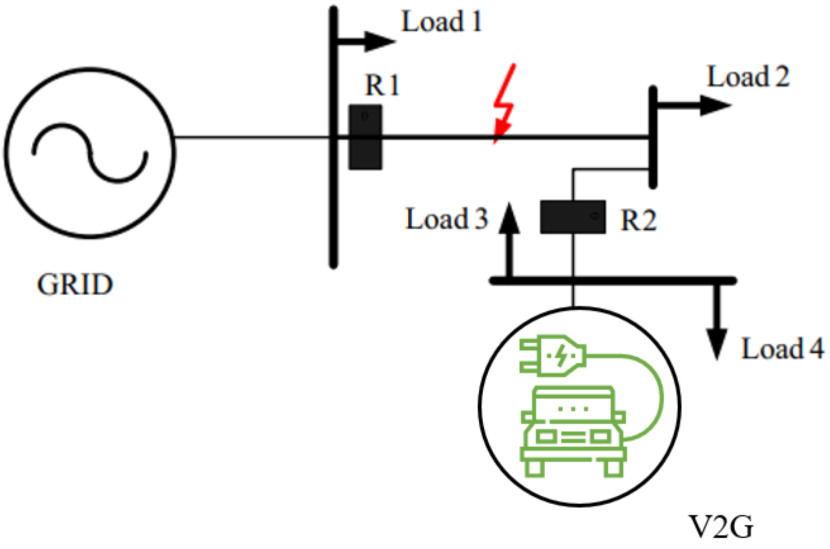


*Figure 8:3: Unintentional islanding*

## 8.3 Protection coordination schemes for distribution system with V2G integration

The conventional strategies for protection and the associated benefits and challenges are provided in

Table 8.1.

*Table 8.1: Conventional protection strategies*

| Technique | Description | Advantages | Limitations |
|---|---|---|---|
| Overcurrent relay (OCR) | Relay trips when current exceeds threshold | Relay coordination on basis of current value detected | Protection blinding, sympathetic tripping and sensitivity issues |
| Directional overcurrent relay (DOCR) | Relay trips for current in specific direction | Can detect bidirectional faults, preferred for mesh networks | Costlier compared to non-directional OCR |
| Differential relays | Performs well for bidirectional and high impedance faults | Can protect radial system from bidirectional power | Error in measurement values of current affects the protection sensitivity |

| | | | |
|---|---|---|---|
| Adaptive over current based protection for distribution networks | It continuously tracks local data (current and voltage) and recalculates the relay characteristics in accordance with the network topology. | Applicable for both grid connected and islanded | Performance compromised under sudden load change or inrush current |
| Adaptive-relay-recloser-fuse coordination | relay/recloser and fuse current are compared | Applicable for both synchronous and inverter based DGs | Can change fast curve of recloser undesirably |
| Voltage based protection | Terminal voltage during low fault levels is observed using symmetrical components | Generates electrical signature when fault occurs | Expensive |

## 8.4 Case study

### 8.4.1 System modelling

To analyze the impact of EV integration on the protection schemes of the distribution network a real-life distribution network of India has been simulated. A detailed dynamic model of the distribution network has been modelled in DIgSILENT PowerFactory, the details of which are given in Table 8.2.

*Table 8.2: Details of the modelled grid*

| S. No. | Component | Rating | Quantity |
|---|---|---|---|
| 1 | AC voltage source (Mains) | 11 kV, 3-phase, 50 Hz. | 1 |
| 2 | Busbar | 11 kV<br>0.4 kV | 150<br>1159 |
| 3 | Lines | 11 kV | 580 |

| | | | |
|---|---|---|---|
| | | 0.44 kV | 707 |
| 4 | 2-winding transformer | 315 kVA | 3 |
| | | 400 kVA | 4 |
| | | 250 kVA | 7 |
| | | 3000 kVA | 1 |
| | | 630 kVA | 2 |
| 5 | General load | Varying between 1 kW -133 kW | 450 |
| 6 | PV Plants | 28 kVA | 1 |
| | | 90 kVA | 1 |

The developed model is used for the carrying out analysis and impact assessment of EV integration. Typical voltage levels of components in distribution system are 11 kV and 440 V. The system is powered by a 3 phase, 11 kV main grid supply, total 1309 numbers of bus-bars (150 numbers of 11 kV bus-bar and 1159 numbers of 440 V bus-bar), total 1287 numbers of lines (580 numbers of 11 kV lines and 707 numbers of 440 V lines). There are a total of 17 numbers of 3-phase transformers, 470 numbers of general load and 450 numbers of EV loads modeled in form of static generators, one 28 kVA, unity power factor PV plant and other 90 kVA, unity power factor PV plant.

### 8.4.2 Distribution of EVs across feeders

The EVs are connected on the low voltage (440 V) side of transformers. The exact numbers of EVs connected on the low voltage feeders is shown in Table 8.3

*Table 8.3: Distribution of EVs*

| Transformer | Rating | Voltage(kV) | EVs on LV side |
|---|---|---|---|
| 2-winding Transformer | 250 kVA | 11/0.44 | 3 charging points |
| 2-winding Transformer(1) | 250 kVA | 11/0.44 | 4 charging points |
| 2-winding Transformer(2) | 250 kVA | 11/0.44 | 1 charging points |
| 2-winding Transformer(3) | 250 kVA | 11/0.44 | 4 charging points |

| | | | |
|---|---|---|---|
| 2-winding Transformer(4) | 250 kVA | 11/0.44 | 3 charging points |
| Transformer 01 | 315 kVA | 11/0.44 | 0 EVs |
| Transformer 02 | 400 kVA | 11/0.44 | 37 EVs |
| Transformer 03 | 250 kVA | 11/0.44 | 12 EVs |
| Transformer 04 | 3000 kVA | 11/0.44 | 1 EVs |
| Transformer 05 | 250 kVA | 11/0.44 | 40 EVs |
| Transformer 06 | 630 kVA | 11/0.44 | 50 EVs |
| Transformer 07 | 400 kVA | 11/0.44 | 25 EVs |
| Transformer 08 | 400 kVA | 11/0.44 | 64 EVs |
| Transformer 09 | 630 kVA | 11/0.44 | 66 EVs |
| Transformer 10 | 315 kVA | 11/0.44 | 35 EVs |
| Transformer 11 | 400 kVA | 11/0.44 | 21 EVs |
| Transformer 12 | 315 kVA | 11/0.44 | 77 EVs |

### 8.4.3 Impact of EV penetration on the Short Circuit Power and Short Circuit Current of lines

A representation of the modelled distribution grid is provided in Figure 8:4. As can be seen under each transformer different amount of loads (i.e. houses and EVs) are connected. To analyze the impact of EV integration on the short circuit power and short circuit current, faults were introduced at the radial end of distribution feeders and the corresponding impact on the LV side of the respective transformers were studied.

The penetration of EVs have been determined considering the number of households that owns an EV, i.e. 100% penetration implies that each household owns an EV.

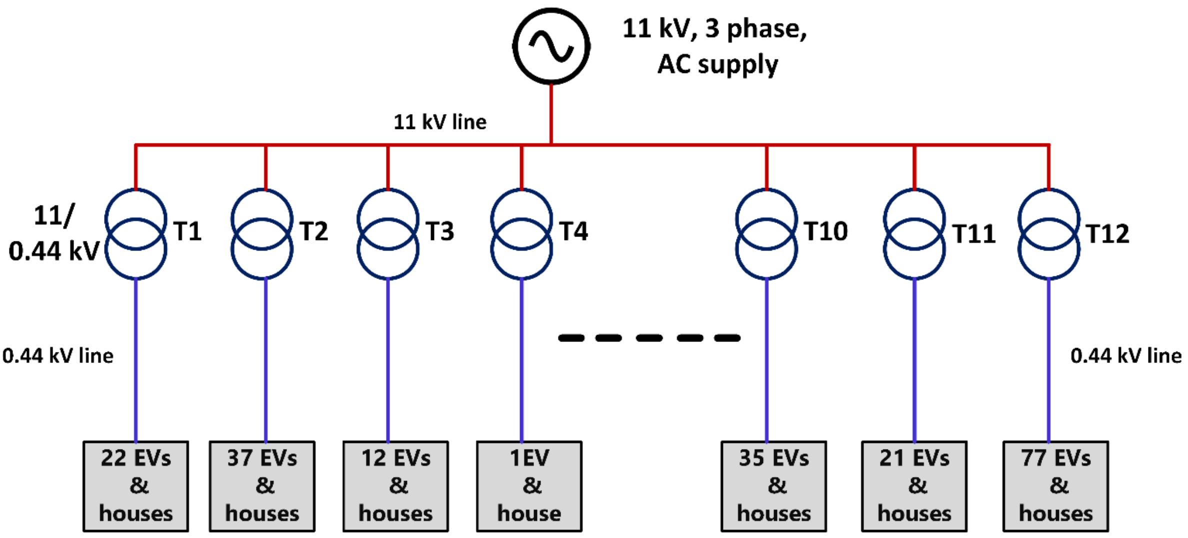


*Figure 8:4: Representative figure of the distribution network*

From Figure 8:5 it can be observed that as the penetration of EV increases the short circuit MVA capacity also increases. As the main supply the short circuit MVA capacity increased from 4.279 MVA for 0% EV penetration to 6.045 MVA for 100% EV penetration. Similarly, for transformer 12, which has the highest number of EVs, the short circuit MVA capacity increased from 2.07 MVA for 0% EV penetration to 2.18 MVA for 100% EV penetration. This implies that as the EV penetration increases in the distribution feeder, the short circuit MVA ratings of the respective circuit breakers also needs to be increased.

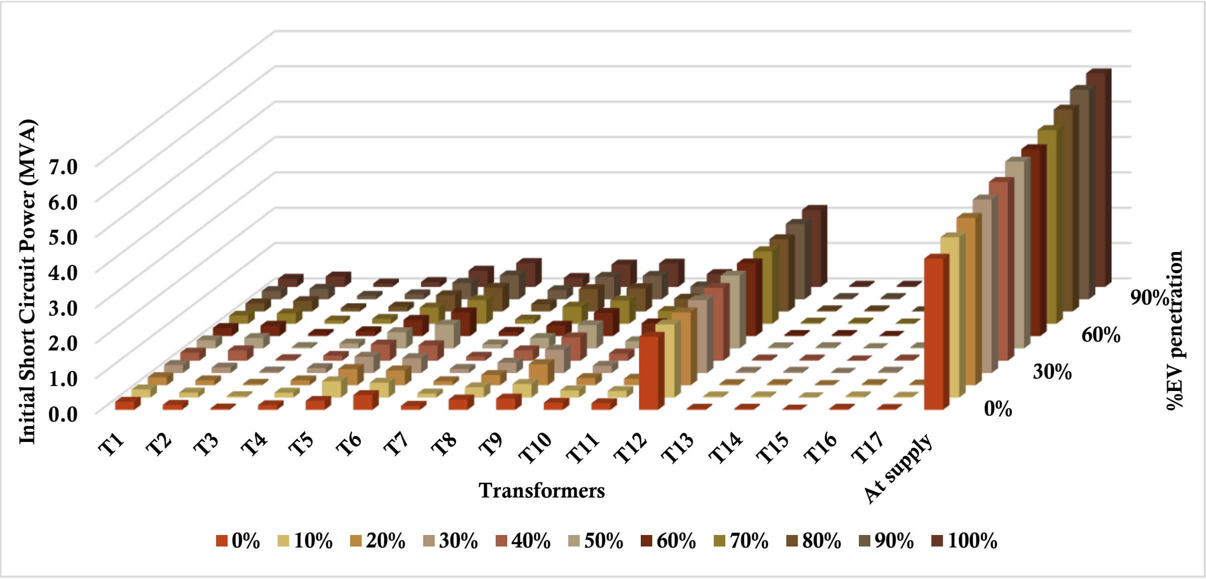


*Figure 8:5: Impact of EV integration on short circuit MVA capacity for LLL fault*

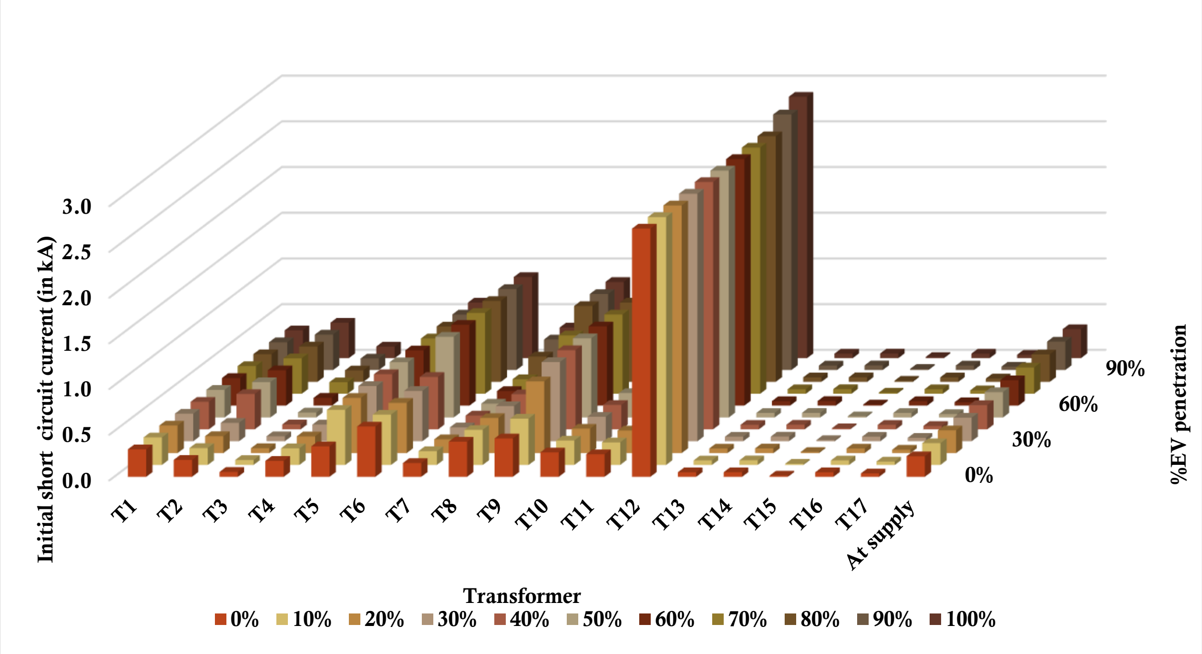


*Figure 8:6: Impact of EV integration on short circuit current for LLL fault*

Figure 8:6, illustrates the impact of EV integration on the short circuit current for an LLL fault. From the figure it can be observed that the short circuit current is more in case of transformers compared to the mains supply, primarily because for the short circuit current is estimated for the LV side of the transformers i.e. 0.44kV, while for the mains supply the short circuit current is determined at the 11 kV voltage level. Also, it can be observed that similar to short circuit MVA capacity, short circuit current also demonstrates a positive correlation with the EV penetration. Also, the highest short circuit current is observed for transformer 12.

## 8.4.4 Impact of EV integration on the pick-up current of relay

With the consideration of EVs, the pickup current setting of relay needs to be modified. Here, pickup current is calculated using the equation below,

$$Pickup\ current = \frac{Full\ load\ current \times Plug\ setting}{CT\ ratio}$$

Where, CT ratio is the ration in the turns ratio in the current transformer and plug setting, which here has been considered as 120%. As the rated current of lines increases with consideration of EVs, the relay pickup current settings need to be increased as shown in Table 8.4. From the table it can be observed that without any EV, the full load current for transformer 12 is around 517.3 A, leading to a pickup current of 620.76 A. However, with EV integration, the full load current of the transformer increased to 1009.8 A. So accordingly th pickup current also increased to 1211.76 A, which reflects almost a 50% increase in the pickup current setting for the associated relay.

*Table 8.4: Impact of EV integration on pickup current setting of relay*

| Transformer (11/0.44 kV) | Without EVs | | | With 100% EV penetration | | | Fault location |
|---|---|---|---|---|---|---|---|
| | Full load current(A) | Fault current (A) | Pickup current (A) | Full load current(A) | Fault current (A) | Pickup current (A) | |
| **Line at Mains** | 138.5 A | 218.7 A | **166.20** | 260.3A | 320.4 A | **312.36** | Bus 189 |
| **T1** | 143.1 A | 151 A | **171.72** | 309.2A | 312 A | **371.04** | Bus 189 |
| **T2** | 186.9 A | 2805 A | **224.28** | 391A | 2825 A | **469.2** | Bus 546 |
| **T3** | 55 A | 1255 A | **66.00** | 128.7A | 1265 A | **154.44** | Bus 614 |
| **T4** | 176.3 A | 1183 A | **211.56** | 184 A | 1254 A | **220.8** | Bus 573 |
| **T5** | 340.6 A | 2375 A | **408.72** | 619.1 A | 2519 A | **742.92** | Bus 72 |
| **T6** | 561.8 A | 3295 A | **674.16** | 904 A | 3396 A | **1084.8** | Bus 158 |
| **T7** | 154.4 A | 2067 A | **185.28** | 314.1 A | 2130 A | **376.92** | Bus 795 |
| **T8** | 392.1 | 1034 A | **470.52** | 846.7 A | 1360 A | **1016.04** | Bus 540 |
| **T9** | 423.9 A | 1192 A | **508.68** | 874.8A | 1157 A | **1049.76** | Bus 677 |
| **T10** | 273 A | 1509 A | **327.60** | 486.3 A | 1611 A | **583.56** | Bus 959 |
| **T11** | 249.2 A | 3125 A | **299.04** | 393.9 A | 3148 A | **472.68** | Bus 543 |
| **T12** | 517.3 A | 2718 A | **620.76** | 1009.8 A | 2859A | **1211.76** | Bus 189 |

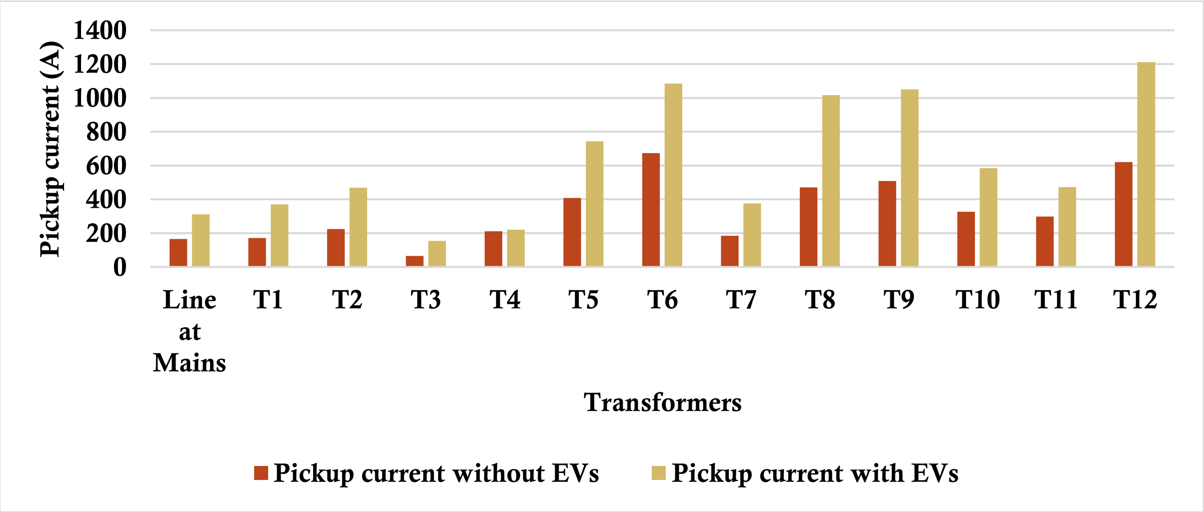
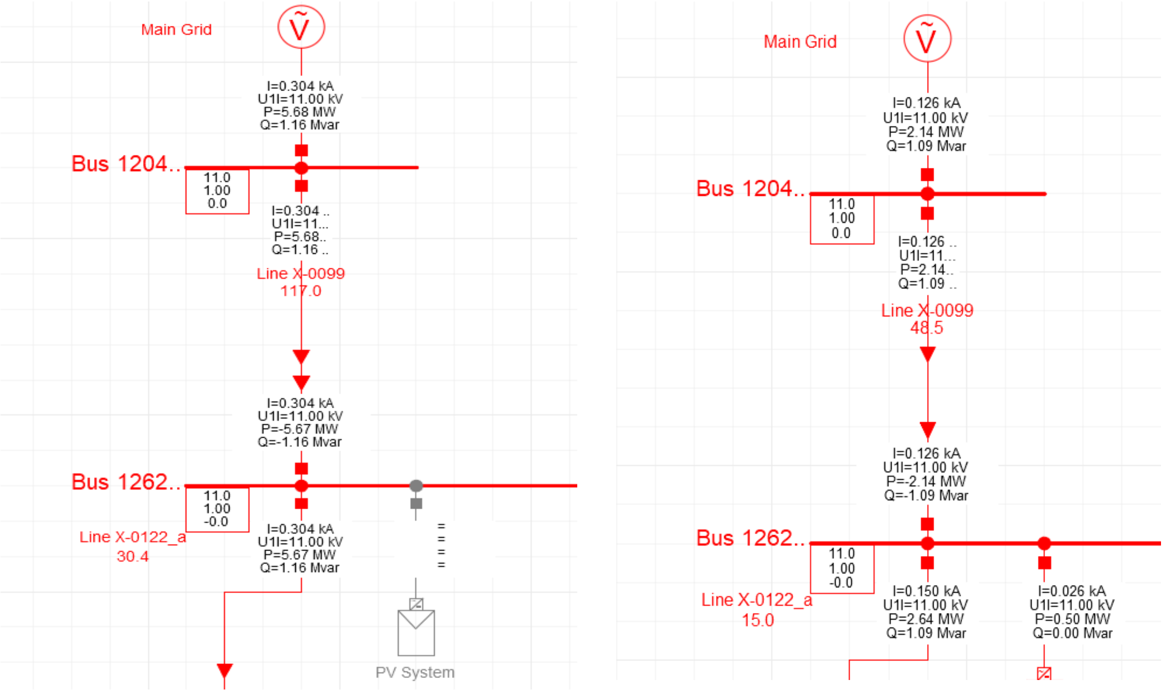


*Figure 8:7 Impact of EV integration on pickup current settings of relay*

## 8.4.5 Protection Blinding

Figure 8:8 shows a zoomed in portion of the distribution grid for illustration of the protection blinding issue. In Figure 8:8 (a), there are no DGs connected, so the current flowing from the mains is around 0.304 kA which flows through the line X-00999. With addition of DGs in the network as shown in Figure 8:8 (b), the current drawn from the mains decreases.



(a)

(b)

*Figure 8:8: Zoomed in section of the distribution network illustrating protection blinding. (a) No DG is connected to the grid and (b) DG is connected across different locations in the grid*

A LLL fault occurs at Line X-0.122. So, as per requirement the breaker between the Line X-0099 and Bus 1204 should open. However, the relay is configured with a pickup current of 600 A, in presence of DGs the relay will not operate as shown in Figure 8:9. This is because, with addition of PV, the net fault current provided by the mains is around 580 A which is lower than the pickup current setting of 600A. However, without any PV, the fault current is around 820 A, as the entire fault current is provided by the mains itself. Thus, due to injection of current from the PV, the relay was blinded to the fault. A similar comment can also be made for EVs providing energy back to the grid.

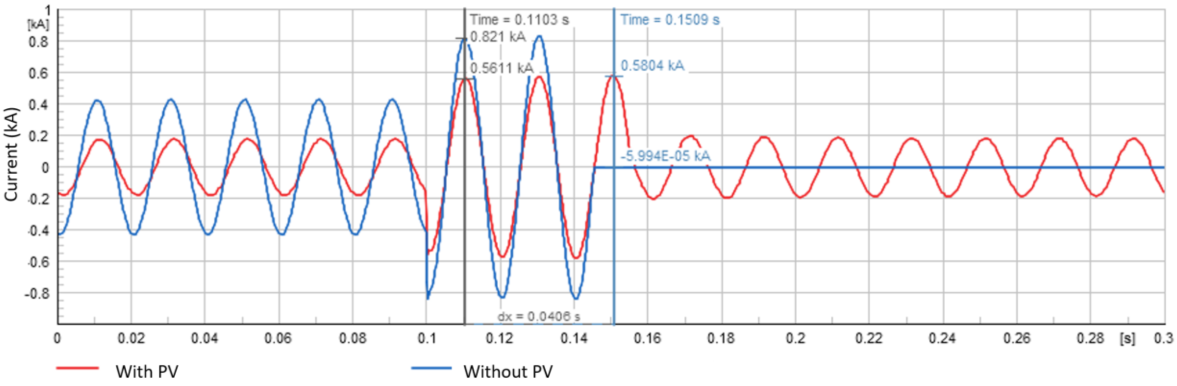


*Figure 8:9: Phase current during fault condition with and without PV*

# Chapter 9. Stakeholder Roles and Responsibilities

V2X application is a multi-stakeholder endeavour, with different roles and responsibilities for each participant. The different stakeholders involved with the different V2X applications have been shown in Figure 9:1

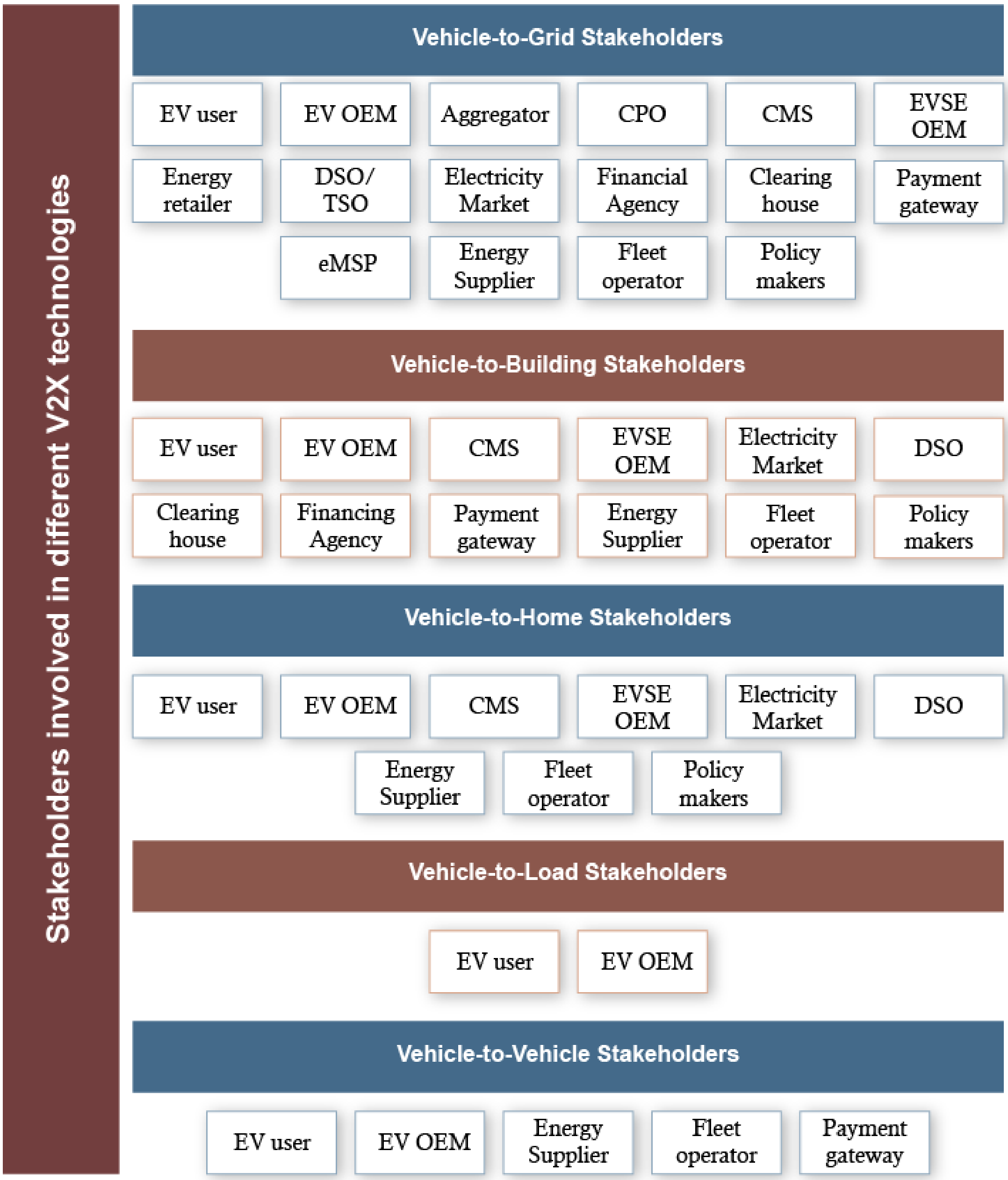


*Figure 9:1 Involvement of different stakeholders for different V2X applications*

### 1. EV user

The success of V2X lies largely with the advocacy of V2X by the EV users. It has been demonstrated by numerous studies that most EV users are generally oblivious of V2X technology, primarily due to lack of awareness[130]. This lack of awareness makes the implementation of V2X difficult. So, it is imperative to educate the EV user base on the benefits of V2X so that they are more engaged with V2X applications are willing to participate.

### 2. OEMs

The role of OEMs is paramount in the success of V2X. To enable V2X, there is requirement of V2X capable EVs and EVSEs. However, as of now very few OEMs provide V2X capable hardware[131]. This is mainly because of the current lack of awareness and interest on V2X among the general public. It is expected that as the market matures more OEMs would be willing to develop V2X capable hardware.

### 3. Aggregator

The role of aggregators is to combine multiple V2X resources and pool them together into a single entity that can participate in the different energy market products. In most markets, there is a minimum bid size required for participation. As a single EV does not have enough capacity to be eligible for participating in the market by itself, multiple EVs needs to be aggregated together. Aggregators then participate in the market products as one single entity, and they control the scheduling of the individual EVs based on the grid and user requirements.

### 4. Energy Distribution Company/Retailer

The role of the energy distributor/ retailer is to facilitate the provision of uninterrupted good quality power to its consumers. In case of an energy retailer, its business is primarily related to transaction of energy. It buys energy from the national energy pool (either by participating in the energy market or through other bilateral contracts) and sells power to the consumers, while deriving a profit though this transaction. However, energy distribution companies are also in the business of ensuring the grid is in a stable operating condition. So, it monitors and ensures that the distribution grid itself is healthy while also delivering energy to its consumers.

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[130] Noel, Lance, Andrea Papu Carrone, Anders Fjendbo Jensen, Gerardo Zarazua de Rubens, Johannes Kester, and Benjamin K. Sovacool. "Willingness to pay for electric vehicles and vehicle-to-grid applications: A Nordic choice experiment." Energy Economics 78 (2019): 525-534.

[131] This is changing fast, with several OEMs offering/planning to offer bidirectional vehicles such as Nissan, Mitsubishi, Lucid, Hyundai, Volkswagen, Renault, Ford, General Motors, Rivian etc.

### 5. CPO

The CPO or the Charge Point Operator is tasked with maintaining and operating a charging station. Their business model also largely revolves around delivering energy to the EVs. They buy the power from the energy retailers/DISCOMs and sells them to the EV users. In V2X they can increase their revenue, by also earning when the EVs are used to help support he grid.

### 6. Grid Operator (TSO/DSO)

The role of the grid operator is to maintain the grid stability and ensure reliable delivery of power to different consumers. They track the operations of the different grid infrastructure and make sure that all the sub systems in the grid are functioning at their optimum capacity. With the advent of increased DER deployment such as EVs (V1G/V2G), rooftop solar, BESS etc. the responsibilities of system operators have increased. They are now also responsible for undertaking new services such as peak load management through DERs, network congestion management, procure voltage support from the DERs, as well as use data to increase DER penetration[132].

### 7. Energy market

Energy markets are a relatively newer stakeholder in the energy ecosystem. The energy markets are regulated markets that specifically deal with trading of energy between the suppliers (generating stations) and consumers (distribution companies, industries and large consumers). In regard to V2G, these markets need to design conducive products that enable aggregated EVs to participate in the different market products[133].

### 8. Payment manager

The payment manager oversees the financial aspects of the V2G applications. As there are different stages where value is being extracted, so for each of these stages the payment manager(s) needs to ensure that the financial transactions are smooth between the involved parties. Different payment managers can oversee the financial aspects for the different V2G layers as given in Figure 9:2.

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[132] IRENA. "Future Role of Distribution System Operators", 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Landscape_Future_DSOs_2019.pdf?la=en&hash=EDEBEDD537DE4ED1D716F4342F2D55D890EA5B9A

[133] Energy markets are generally regulated, and as such they can only design products in the purview of the existing regulations in the region. So, here it is implied that post the regulatory issues are clarified the markets needs to adopt the same and design new products accordingly.

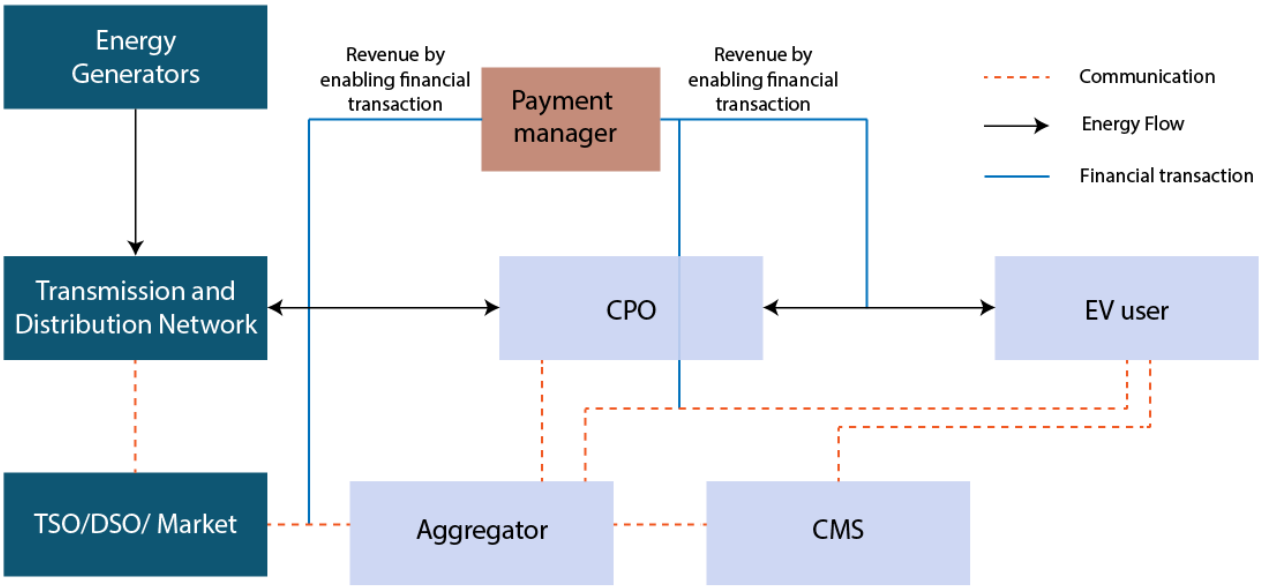

*Figure 9:2: Role of payment manager*

## 9. Telecom operator

One of the critical enablers of V2X technology is the requirement of robust communication between the different involved entities. As V2X is a highly collaborative endeavor, the role of communication is significant. It is the responsibility of the telecom operator to provide a secure and reliable communication channel to facilitate the data transmission. If ancillary services are also being provided using V2X, the importance of reliability of the communication channels further increases.

## 10. Policy Maker

In order to make V2X a reality, the role of policy makers is paramount. The current market conditions are ill suited for V2X primarily due to lack of user awareness, high implementation cost, regulatory barriers etc. Here, it is the role of the policy makers to in designing and implementing policies that can facilitate the growth of V2X applications. They need to create an efficient ecosystem that encourages the adoption of V2X technologies, facilitates investment opportunities and ensures proper system operation.

### 11. Regulatory Authority

The regulatory authorities are needed to create adequate regulations pertaining to V2X. These include interconnection regulations for connection of V2X resources with the grid, safety regulations, energy market regulations that enable V2X to participate in the energy markets as well as different tariff structures suitable for V2X. Adequate regulations are one of the critical challenges for implementation of V2X. Here it needs to be mentioned that regulations have higher importance for V2G services as compared to V2H, V2V and V2L, mainly because in V2G the vehicle is connected to the main grid. While in V2H, V2V and V2L it operates in its own microgrid, so baring the safety regulations, the grid interconnection regulations are not required.

### 12. Standard Issuing Authority

The successful growth of V2X also rests on the availability of V2X capable hardware for which adequate standards needs to be in place. These standards may include V2X capable charger standards, communication standards, grid integration and safety aspects. International institutions like as the International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), CHAdeMO and Society of Automotive Engineers (SAE) have been crucial in helping stakeholders in this industry develop V2X standards internationally.

### 13. Testing and Certification authority

Post the creation of standards and regulation, there also needs to be testing and certification authority that ensures that the developed products follow the necessary standards. All current and future EV models must pass rigorous testing for homogenization from both a vehicle and individual component point of view in order to guarantee safety and compliance with applicable standards and regulations.

# Chapter 10. Conclusion

With the evolution of the transportation sector, a rapid uptake of electric vehicles in many parts of the world including India have been observed. While the increased penetration of EV can potentially introduce different challenges if not properly managed, electric vehicles and its battery storage can provide a range of benefits for the EV user, the electrical grid operator and the society at large.

In this report, the different applications of EVs with bidirectional charging capability and the services that it can provide have been presented. From powering small isolated electric loads through V2L, to powering up a small residence using V2H or a building using V2B, or even the electrical grid through V2G, the potential of V2X is wide and varied. Each of the applications have their own range of economic benefits and unique requirements to extract the same. While applications such as V2L might have much lower value as compared with V2H or V2G, its implementation requirements are also much simpler. For implementation of V2G and the different associated services, an overall ecosystem design would be required with close cooperation between the different involved stakeholders. The participation of distributed resources in grid support services have led to the development of VPPs, of which V2G can be an integral member.

While, theoretically V2X presents itself as an excellent candidate for solving a myriad of users' issues, its economic viability in an Indian context needs to be explored. In Report 2 of this series, multiple techno-economic analysis has been carried out to determine the viability of V2G, V2H and V2B in the Indian ecosystem. Techno-economic analysis of different applications using V2X such as increased RE integration, energy arbitrage, voltage and frequency support services and behind-the-meter applications have been undertaken in the study.

Moreover, in the current EV ecosystem there are multiple challenges in V2X adoption. These challenges can broadly be classified into regulatory, technical, economic and societal challenges. Mitigation of the said challenges would need a concentrated and unified effort from the different stakeholders in the ecosystem. The way forward for implementation of V2X in India have also been reported in Report 2.

# Annexure

## List of stakeholder consultations

- The Mobility House
- IoTecha
- Enel Group
- Fermata Energy
- CharIN e.V.
- CERC
- Dr. Indradip Mitra (GIZ)
- Ms. Sahana L. (GIZ)
- TATA Power
- BYPL

# V2G Field Trials by IIT Bombay

To extend the findings of this study, Grid Integration Lab IIT Bombay has undertaken two field pilot studies to demonstrate various V2X applications, with primary focus on V2G, V2H and V2V applications. The first pilot is primarily focussed on V2G, V2H applications, while the second pilot is focussed on Renewable Energy based V2G and V2V demonstration in a public charging station. These two field pilots are expected to demonstrate V2X technology and its capability along with finding challenges in implementation of V2G in Indian EV ecosystem. Dissemination events on the findings of V2G field trials are planned to be conducted next year. To stay tuned about the progress of the V2G field trials, interested persons may visit '*V2G Field Trials*' tab of **Grid Integration Lab IIT Bombay** website.

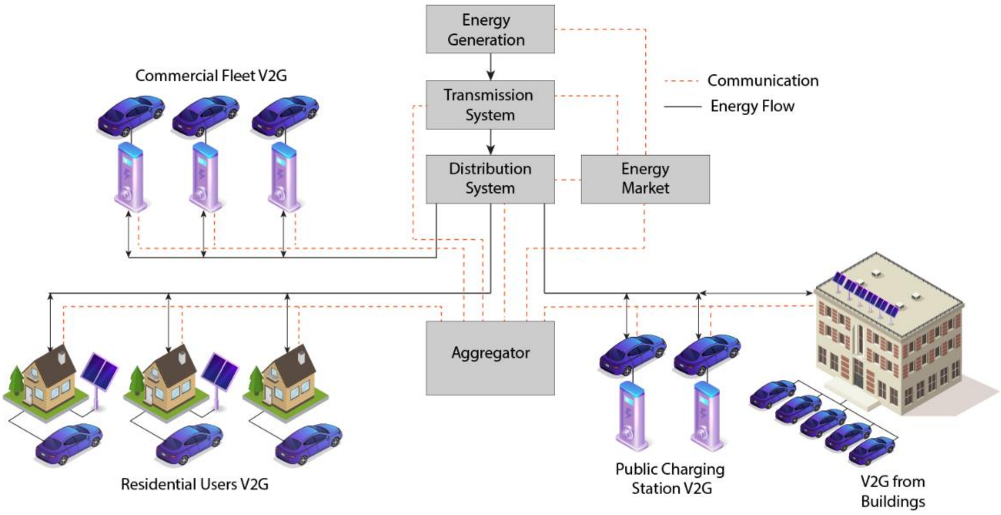

*Figure A:1. V2G architecture*

*Figure A:2. V2H system*[4]

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