

Smart charging in India: Study on EV freight corridor and grid infrastructure for managed charging integration

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Acknowledgement

This study was commissioned as part of the global study undertaken by The Regulatory Assistance Project (RAP) in collaboration with the International Council on Clean Transportation (ICCT). The study focuses on assessing the economic and environmental benefits of managing EV charging in India as part of the other global EV markets.

About MP Ensystems

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List of abbreviations

EFVs	Electric Freight Vehicles
DISCOMs	Distribution Companies
EVs	Electric Vehicles
DSO	Distribution System Operator
MCDM	Multi-Criteria Decision-Making
ToD	Time-of-Day
ToU	Time-of-Use
PGE	Portland General Electric
PV	Photovoltaic
PEV	Plug-in Electric Vehicle
WPD	Western Power Distribution
ACoS	Average Cost to Serve
ACC	Average Cost to Charge
APU	Average Profit to Utility
ACS	Average Cost of Supply
RE	Renewable Energy
LT	Low Tension
HT	High Tension

Definitions and terminologies used

Term	Short Definition
Average Cost to Serve	Cost incurred by utility in different time periods of the day, aggregated across all customer classes, taking into account production, transmission, and distribution costs.
Average Cost of Supply	The average cost incurred by a utility to generate and deliver electricity at different times of the day per specific customers, taking into account production, transmission, and distribution costs.
Average Profit to Utility	The average financial gain or profit earned by a utility after covering its costs, typically calculated as revenue minus expenses.
Ancillary Service	Additional services provided by the power grid to support the stability and reliability of the electrical system, including services like frequency regulation and spinning reserves.
CFPR	Continuous Fuzzy Preference Relations (CFPR) is a concept related to decision-making under uncertainty. It involves modelling preferences using fuzzy logic in a continuous domain, allowing decision-makers to express their preferences in a more nuanced and flexible manner. CFPR provides a framework for dealing with subjective evaluations and imprecise information when making decisions.
Fuzzy TOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is an extension of the classical TOPSIS method, which incorporates fuzzy logic to handle uncertainty and vagueness in decision-making processes. This approach allows for the consideration of imprecise or vague information in determining the best alternative among a set of options.
Grid Congestion Management	Strategies and measures implemented to alleviate congestion on the electrical grid, ensuring efficient and reliable power transmission.
G2V (Grid-to-Vehicle)	The process of charging electric vehicle batteries using electricity from the grid, ensuring a steady and reliable power supply to the vehicles.
Load Levelling	The process of balancing electricity supply and demand to maintain a stable and reliable power system, often achieved through energy storage or demand response programs.
MULTIMOORA	This term stands for Multi-Objective Optimization on the Basis of Ratio Analysis. It's a decision-making technique that integrates the benefits of both MOORA (Multi-Objective Optimization by Ratio Analysis) and MCDM (Multi-Criteria Decision Making) methods. MULTIMOORA assists in decision-making processes by evaluating alternatives based on multiple criteria and objectives, using ratio analysis to rank them accordingly.
RE Integration	The seamless integration of renewable energy sources, such as wind and solar, into the existing power grid, often involving smart grid technologies.
Time of Use/ Time of Day (ToU/ToD)	ToU/ToD is a tariff structure in which different rates are applicable for use of electricity at different time of the day. The terms ToD and ToU are used interchangeably.
V2G (Vehicle-to-Grid)	A technology that enables electric vehicles to discharge electricity back to the grid, providing grid support during peak demand or other grid conditions.

V2X (Vehicle-to-Everything)	Encompasses various interactions between electric vehicles and the broader energy ecosystem, including V2G, G2V, and other connections to buildings and the grid.
Voltage Support	Techniques and equipment used to regulate and maintain voltage levels in an electrical system, ensuring stability and reliability.

Terms used In model analysis	
Time frame	Span of analysis to project cost implications over time
Power generation cost	Utilizing IEX market slot-wise rates as a reference for ACS, considering various utility costs associated with serving energy to consumers, including variable energy charges
Charging tariff	Assumed EV tariff values
Average cost to serve	IEX market rate values (24hrs cycle)*total charging
Average cost to charge	Assumed EV Tariff * Total charging demand
Average profit to utility	Average cost to charge – Average cost to serve

Executive summary

The comprehensive report by the MP Ensystems team delves into the dynamics of integrating Time-of-Day (ToD)¹ pricing strategies in Electric Vehicle (EV) charging within India's energy landscape. Through case studies, surveys, modelling exercises and stakeholder discussions, the report explores the impact of tariff structures on EV charging, grid utilization, and Renewable Energy (RE) integration.

The literature review highlighted that smart charging and ToD strategies offer effective solutions for transportation electrification and grid decarbonization. They can mitigate increased grid operating costs and reduce renewable energy curtailment. By leveraging the flexibility of EV charging, utilities can better manage charging loads through ToD pricing models. ToD incentives, particularly when paired with user-friendly smart charging apps, effectively encourage shifting demand away from evening peaks.

Engaging with stakeholders through surveys, site visits provided invaluable insights into the **real-world dynamics** into the sector. Some of those insights were:

1. Substation capacity and integration of EV charging stations: Stakeholder meetings indicate that most substations currently have sufficient capacity for new connections. Adjustment of substation capacity, typically through transformer installations or removals, effectively addresses overloading or underloading issues. Connection of bulk loads, ranging from 1 MVA to 40 MVA, hasn't led to grid congestion or stability concerns for DISCOMs.

2. Peak usage patterns and charging schedule shifts: Visit to an industrial load substation reveals significant usage peaks from 9:00 AM to 6:00 PM, coinciding with manufacturing operational hours. Substation level peak periods can vary depending on the type of consumers connected, so generic strategy cannot be suggested to reduce substation overloading.

3. Ground surveys and driving behaviours: Heavy Duty Vehicles (HDVs) operate on an ad-hoc basis, with asset being used as and when there is demand for freight. The only constraint to their usage in and around Delhi is the “ban time”². This presents a challenge in estimating their stoppage/ resting time and hence, charging demand.

4. Installation of EV charging stations near highways: Consultations reveal that most EV freight fleets are expected to have dedicated captive charging stations at logistic parks or base stations. Public charging stations along highways are envisioned primarily for opportunity charging during vehicle rest stops.

5. Challenges with opportunity charging: Opportunity charging presents challenges due to the relatively short plug-in times for EVs, imposing strict limitations on managing charging loads in this context.

6. Further study requirements: Understanding components of electricity supply cost and tariff calculation is crucial for studying tariff, charging demand, and other relevant parameters.

A **modelling exercise** was conducted to further explore the feasibility of shifting charging demand to solar hours and the relationship between electricity supply cost, tariffs and cost to charge and related parameters. The modelling aimed at shifting the estimated charging demand to solar hours (from partially to fully, illustrated by three scenarios) and understanding the effects of this shifting and its impact on grid from an economic perspective.

2 cases were made giving a total charging demand for 2023, 2025, 2027, 2030 and BAU scenario. Within each case, 3 scenarios namely scenario 1, scenario 2, scenario 3 were modelled for shifting of EV charging demand in solar hours.

¹ ToD tariff means to encourage electricity consumers to shift their energy usage away from peak periods when demand and costs are high and towards off-peak periods when demand and costs are lower

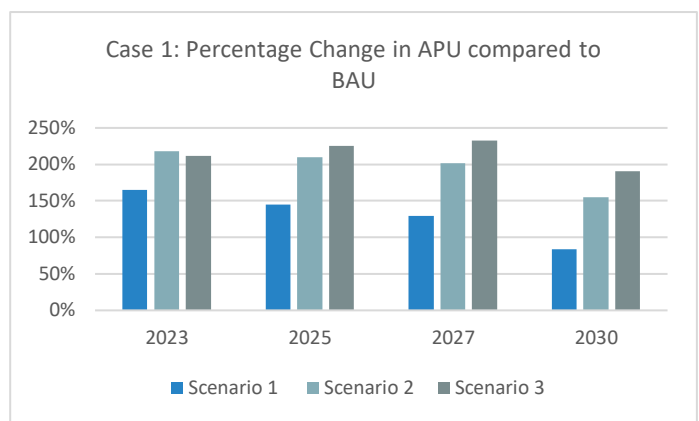
² The time slot for entry and exit restrictions for freight vehicles in Delhi

For each scenario, a threshold demand was calculated. And the charging demand in non-solar hours above threshold demand is shifted in solar hours.

Threshold value is calculated for each scenario for charging profile of 24 hrs being average - for scenario 1, Average/2 for scenario 2 and 0 (100% shift of charging demand to solar hour for scenario 3.

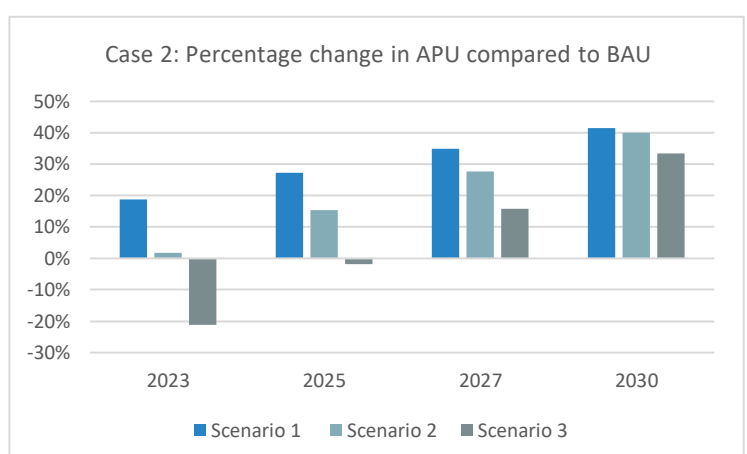
- **Case1:** Depot charging is presumed to occur exclusively during night-time hours, specifically from 22:00 PM to 6:00 AM, spanning a continuous period of 8 hours. Charging demand from fast and ultrafast charging is also added to get total charging demand³.
 - **Average profit to utility (APU) for all the scenarios is better than the BAU scenarios in all the years considered.** For 2023 and 2025 scenario 2 gives the highest increase in APU change and for 2027 and 2030 scenario 3 shows the maximum profit.

APU (INR/day)				
	BAU	SCN 1	SCN 2	SCN 3
2023	35248.38	93511.12	111951.7	109713.6
2025	61424.71	150542.4	190132.7	199814.1
2027	184842.5	423408.8	558164.7	614992.5
2030	1005654	1850151	2562391	2921462



- **Case2:** Depot charging occurs during periods of low traffic flow along the corridor, as determined by data from traffic surveys. Based on this data, two time slots have been pinpointed for depot charging: 7:00 AM to 11:00 AM and 4:00 PM to 8:00 PM.
 - For case 2, scenario 2 can result in negative change in APU compared to BAU scenario. So the shifting of all the demand to solar hours might not be feasible from utilities perspective.

APU (INR/day)				
	BAU	SCN 1	SCN 2	SCN 3
2023	136163.5	161804.3	138473.2	107468.5
2025	200790.8	255713.6	231644.6	197088.1
2027	526336.1	709534.8	672301.9	609189.1
2030	2176896	3077948	3049926	2904431



The results of the model showed mixed outcomes, highlighting the potential and the complexities involved in aligning charging demand with solar generation. Adjusting the model to assess cost implications and changing tariff rates and

³ RAP, ICCT (October 2024), Optimising electric heavy duty truck charging on freight corridors in India

offering rebates for shifting demand to solar hours is crucial for utilities. Incentivizing consumers to align charging demand peak periods with solar generation can reduce strain on the grid during peak hours and maximize solar energy utilization, benefiting the environment and lowering energy costs.

However, understanding the price elasticity of demand for shifting freight EV charging demand in the solar period also requires a detailed analysis of consumer behaviour and preferences, as well as an examination of the potential benefits and costs. Once this analysis is completed, DISCOMs can offer rebates or incentives to encourage consumers to shift their electricity usage to off-peak solar hours, ultimately increasing revenue and promoting sustainable energy practices.

From the study we were able to draw insights on key factors for successful freight vehicle charging implementation, which include emphasizing the influence of truck drivers' behaviour and movement patterns. **In case the off peak period and solar generation period coincides, incentivizing consumers to shift their electricity usage to off-peak solar hours allows DISCOMs to reduce the strain on the electricity grid during peak hours and maximize the use of solar energy.**

The study underscores the need for adequate charging infrastructure during daylight hours and proposes exploration of wind power as a night-time energy source. Smart charging strategies must account for drivers' discretionary stoppages. Insights also include the importance of solar PV integration for cost reduction, the role of smart tariffs in sharing benefits, and the relatively minor impact of EV charging on the grid in the current scenario. ToD pricing can manage EV demand effectively, with a focus on aligning charging with solar availability and accommodating diverse stopping patterns. Overall, integrating renewable energy sources with DISCOMs and addressing driver behaviour are crucial for sustainable freight transportation.

Scope and objectives of the report

The report aims to explore and analyse the value of smart charging of electric trucks along a defined freight corridor from the lens of managed charging, ToD pricing mechanisms, and the resulting reduced grid upgradation costs in the Indian context.

For getting a detailed understanding of impact of ToD pricing mechanisms, an excel model was created and by examining different scenarios through the ToD model we aim to offer insights into the impact of use of RE and managed charging.

Through a comprehensive analysis of industry reports, case studies, and tariff orders and stakeholder consultations, this report aims to achieve the following goals:

- To identify and analyse key trends and developments in smart charging, managed charging, and ToD pricing mechanisms within the Indian EV charging infrastructure landscape.
- To assess the implications of these trends on stakeholders, including EV owners, energy utilities, policymakers, and environmental advocates, as well as on the broader energy sector and sustainable transportation initiatives in India.
- To provide recommendations and insights that can be used by stakeholders like policymakers, energy regulators, utility providers, and EV charging infrastructure developers to navigate challenges and capitalize on opportunities related to the use of RE and managed charging strategies, as well as the implementation of ToD pricing mechanisms.
- By addressing these objectives, this report seeks to contribute valuable insights and facilitate informed decision-making in the Indian energy sector and sustainable transportation initiatives, ultimately fostering the transition towards a more sustainable and efficient EV charging infrastructure.

Structure of the report

The flow of the report follows a structure as given below:

Chapter 1: Introduction: In this introductory chapter, the report sets the stage for an in-depth exploration of smart charging, focusing on managed charging and ToD pricing mechanisms within the Indian context. It outlines the overarching objective of providing a comprehensive understanding of these concepts and their interplay with Renewable Energy (RE) integration in the context of managed charging strategies. The chapter also highlights the significance of understanding grid upgrade cost calculations as a crucial component of this analysis.

Chapter 2: Case studies | Impact of ToD pricing on EV charging: This chapter presents case studies that delve into the impact of ToD pricing mechanisms on EV charging behaviours, particularly within the Indian context. By examining real-world examples and experiences, the chapter aims to shed light on the effectiveness of different pricing strategies in influencing charging patterns and grid utilization. Moreover, it discusses the role of RE integration in shaping these dynamics, providing valuable insights for policymakers and stakeholders.

Chapter 3: Understanding impact of tariff structures on charging and grid utilization: Building upon the insights gleaned from the case studies, this chapter delves deeper into the impact of tariff structures on EV charging and grid utilization. It reviews state-specific tariff orders in India, analysing how different pricing mechanisms affect charging behaviours and grid dynamics. Special emphasis is placed on understanding the implications of RE utilization within the context of managed charging strategies, offering valuable insights for stakeholders and policymakers alike.

Chapter 4: ToD economic modelling exercise: This chapter details the development and application of an excel model aimed at analysing the economic implications of ToD pricing mechanisms on EV charging behaviour. By simulating various scenarios and examining the outcomes through the model, the chapter provides nuanced insights into the impact of RE utilization and managed charging strategies. It offers a quantitative assessment of the economic feasibility and effectiveness of different pricing mechanisms, informing decision-making processes in the realm of EV charging and grid management.

Chapter 5: Inferences from the study: Finally, this chapter synthesizes the findings and inferences drawn from the entire study, offering a cohesive overview of the research outcomes and their implications. It highlights key insights regarding the impact of ToD pricing mechanisms, RE integration, and managed charging strategies on EV charging behaviour and grid dynamics in the Indian context. The chapter provides actionable recommendations for stakeholders and policymakers.

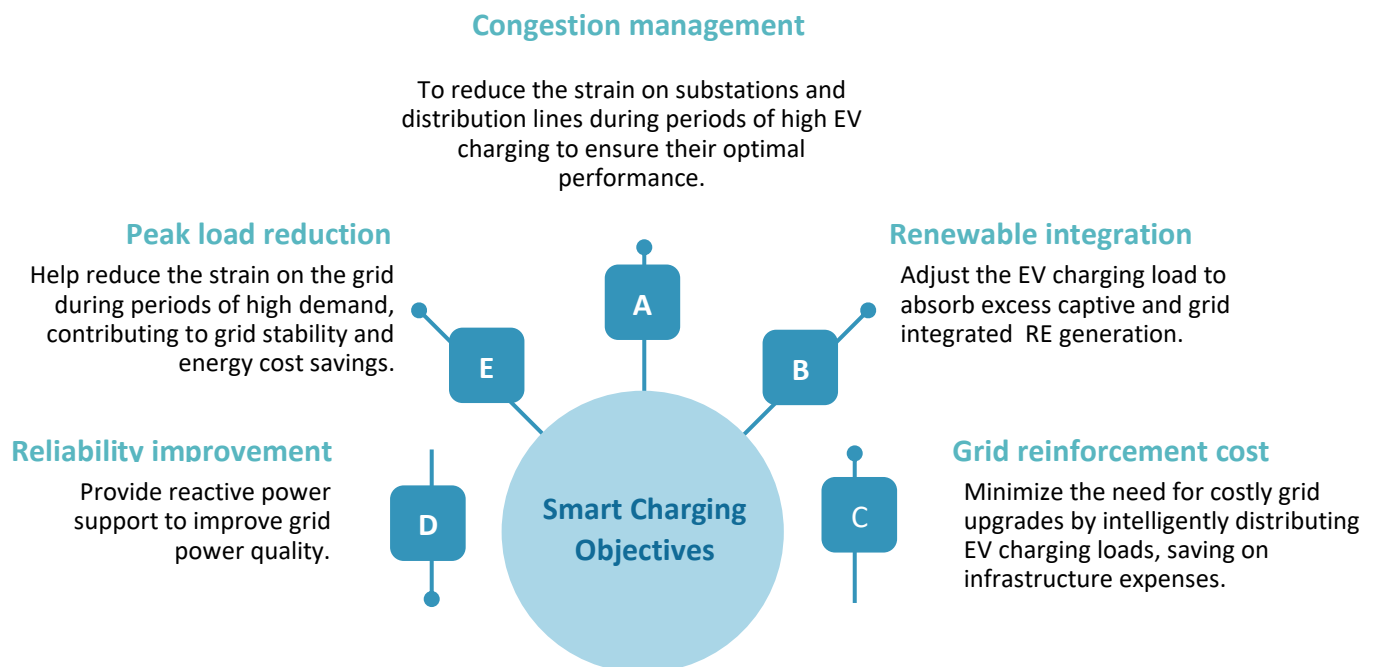
Chapter 1: Introduction to smart charging

Charging electric freight vehicles (EFVs) presents significant challenges due to two primary factors: the need for quick charging and strict time constraints. Fast charging demands a centralized, high-power load and is characterized by heightened load fluctuations due to the shorter charging durations and elevated power requirements. In scenarios with high penetration of electric vehicles (EVs), this demand can result in overloading grid network components. Additionally, the concentrated load associated with fast EV charging can cause voltage instability and frequency challenges within the power grid.

To address these challenges, smart charging strategies can be implemented. Smart charging refers to the optimal or intelligent charging of electric vehicles that adapts to both the conditions of the electricity grid and the needs of EV users. It dynamically regulates the power consumption of EVs based on various triggers to achieve specific objectives, including grid stability, cost optimization, and renewable energy (RE) integration.

Some of the general objectives for smart charging are:

Figure 1: Smart charging objectives



Source: MP Ensystems Research, 2024

Smart charging allows grid operators to manage EV loads efficiently, thus preventing grid congestion and reducing operational costs. In India, **Time-of-Use (ToU) pricing** is particularly emphasized as a key method to encourage off-peak charging. By offering lower electricity rates during off-peak hours—such as times of peak solar energy production or nighttime—ToU pricing reduces the load on the grid during high-demand periods, making energy use more efficient and cost-effective.

Types of Smart Charging Strategies:

- Time-of-Use (ToU)/Time-of-Day (ToD) Tariffs:** Basic pricing structures that encourage EV owners to charge during off-peak hours.
- Unidirectional Controlled Charging (V1G):** Adjusts the charging power dynamically based on grid conditions.
- Bidirectional charging (V2G, V2X):** Allows power to flow between the EV and the grid, enabling vehicles to provide grid support during peak demand.
- Dynamic pricing:** Adjusts electricity prices in real time based on current grid demand and energy availability.

1.1 Smart charging and introduction to impact of EV charging on grid

Smart charging involves efficiently handling the EV loads to minimize the impact of EV integration on the distribution network. We define smart charging in the Indian context as the pattern of charging driven by smart tariffs. Smart tariffs are tariffs that motivate changes in charging patterns that support the goal of minimising system cost, a win-win tariff scenario charged by the DISCOMs to the EV users that reflects available arbitrage between cost of supply and cost of power procurement. We imagine smart charging as a user convenience which would be a reflection of haulage requirements and stoppages. Different smart charging technologies have been proposed to minimise the impact of EV charging on the distribution grid. Smart charging can be implemented through customer responsiveness to price signals, electric vehicle supply equipment (EVSE) responding to control signals from the distribution system operator (DSO) or a central management service⁴. Importantly, it aims to balance these actions while ensuring that the EV battery retains sufficient charge to meet the travel needs of EV users. **Table 1**⁵ summarises the different types of smart charging applications, as developed by a prominent research institute in India.

Table 1: Summary of smart charging application⁶

Application	Control over charging power	Possible uses	Maturity
ToU/ToD tariffs	None	Load levelling	High
Basic control	On/off	Grid congestion management, voltage support, RE integration, load levelling	Partial market deployment
Unidirectional controlled (V1G)	The charging current/power is dynamically changed	Grid congestion management, RE integration, voltage support, load levelling, ancillary service	Partial market deployment
Bidirectional V2G and G2V	Bidirectional flow of power between EV and grid	Grid congestion management, RE integration, voltage support, load levelling, ancillary service	Partial market deployment
Bidirectional V2X	Integration of bidirectional charging and home/building energy management systems	Behind-the-meter optimization, micro-grid optimization	Partial market deployment
Dynamic pricing	Close to real time communication of dynamic electricity price between EVSE and grid	Grid congestion management, load levelling, RE integration,	Partial market deployment

Source: MP Ensystems Research, 2024

GIZ conducted a comparative study of high impact/quality reports that can supplement decision making by the Government of India including State Governments, distribution system operators, transmission system operators,

⁴ Zakir Rather et.al. Electric Vehicle Charging Infrastructure and its Grid Integration in India Status Quo, Critical Analysis and Way Forward, 2022

⁵ The table only aims to provide a summary (and not comparison) of the different types of smart charging applications and its control over charging power, possible uses and maturity

⁶ Zakir Rather et.al., Recommendations for Seamless Adoption of EV Charging Infrastructure in India, 2023

planning and regulatory agencies and other stakeholders (EV industry etc.) to frame, adapt, and/or revise policies, regulations, technical charging standards, communication protocols related to the integration of EV charging infrastructure with distribution and the transmission grid. A part of the study talks about different interventions and evaluating them through a multi-criteria decision-making (MCDM) process⁷. Figure 2 shows the ranking of different interventions.

Figure 2: Overall ranking of technical interventions

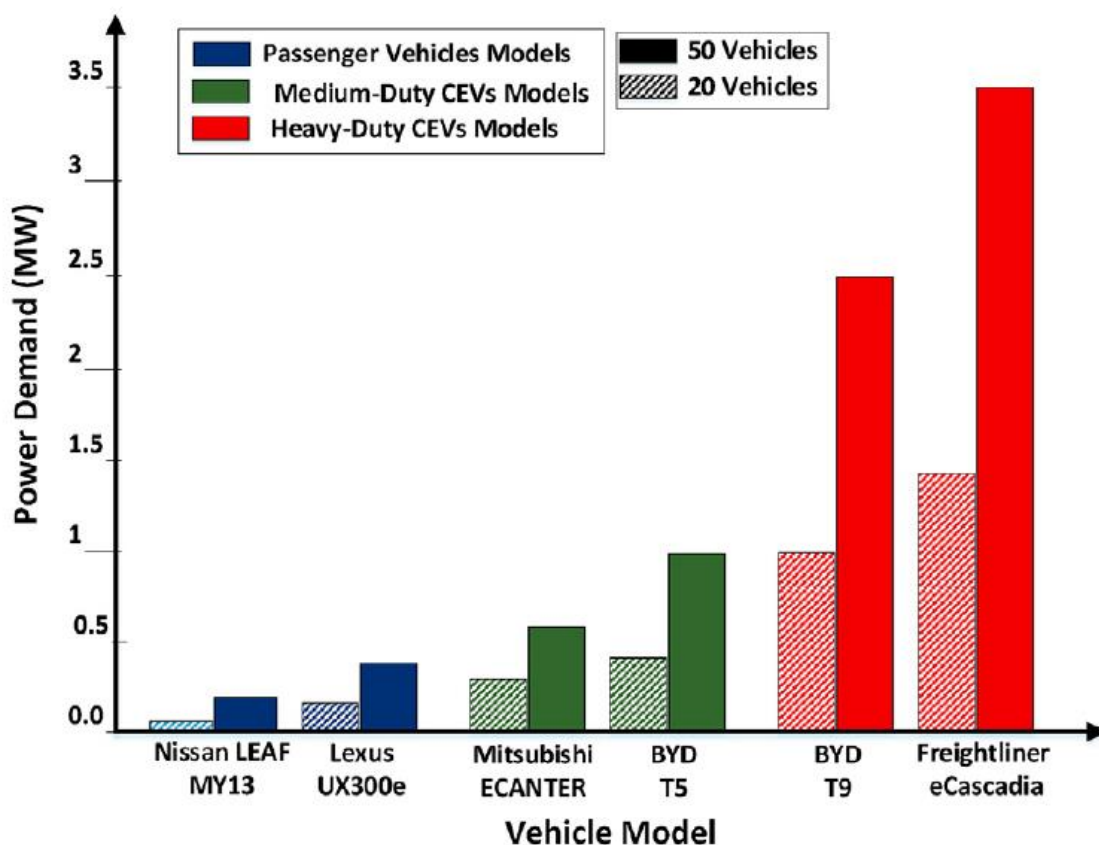
	MULTIMOORA	Fuzzy TOPSIS	CFPR	Final Rank
Time based EV tariffs	1	1	1	1
RE integration	2	2	2	2
Smart Charging – Unidirectional	3	5	3	3
Interoperability	4	3	4	3
Fast Charging Infrastructure	6	4	6	4
Energy market participation for EV	5	7	5	5
Battery Swapping Infrastructure	7	8	7	6
Slow Charging Infrastructure	9	6	9	7
Smart Charging with V2G	8	9	8	8

- The study finds that implementing time based EV tariff (ToD) is the most preferred alternative as it is relatively easier to implement and has high potential impact.
- One recommendation from a study of this nature is to develop a ToD structure on the merit of reduced Average Cost to serve (ACoS) in different time periods optimizing load within the discoms network, reducing backing down of solar and other RE sources and a possibility to reduce investments that would go in system upgrades usually referred as deferred investment.
- ToD tariffs are based on the time of use of electricity by consumers. Consumers incur a higher tariff during the utility's peak hours and receive a rebate during off-peak hours.
- ToD tariff can also be designed to shift the load in solar hours, where the cost to serve is lower which can help DISCOM to minimize the generation cost and minimise the need for storage infrastructure for integrating higher solar generation.

Charging Electric Freight Vehicles (EFVs) poses a complex challenge. EFVs, with their larger battery sizes, require high-power charging infrastructure, significantly increasing peak demand for EFV fleet charging compared to Electric Vehicle (EV) fleet charging, as depicted in Figure 3. Adding to the complexity, EFVs and in general freight vehicles operate on strict schedules, impacting their availability for charging and intensifying the peak demand for EFV fleet charging. Charges for consumers usually consist of per-kWh energy charges along with per-peak-kW demand charges, which are based on the maximum power (KW) needed within specific intervals, typically spanning 15 minutes throughout the month.

⁷ Here MULTIMOORA, Fuzzy TOPSIS, CFPR mentioned in the columns are analysis methods definitions of which are given in the definitions sections in the start.

Figure 3: Comparison of peak demand from EV cars and freight EVs⁸



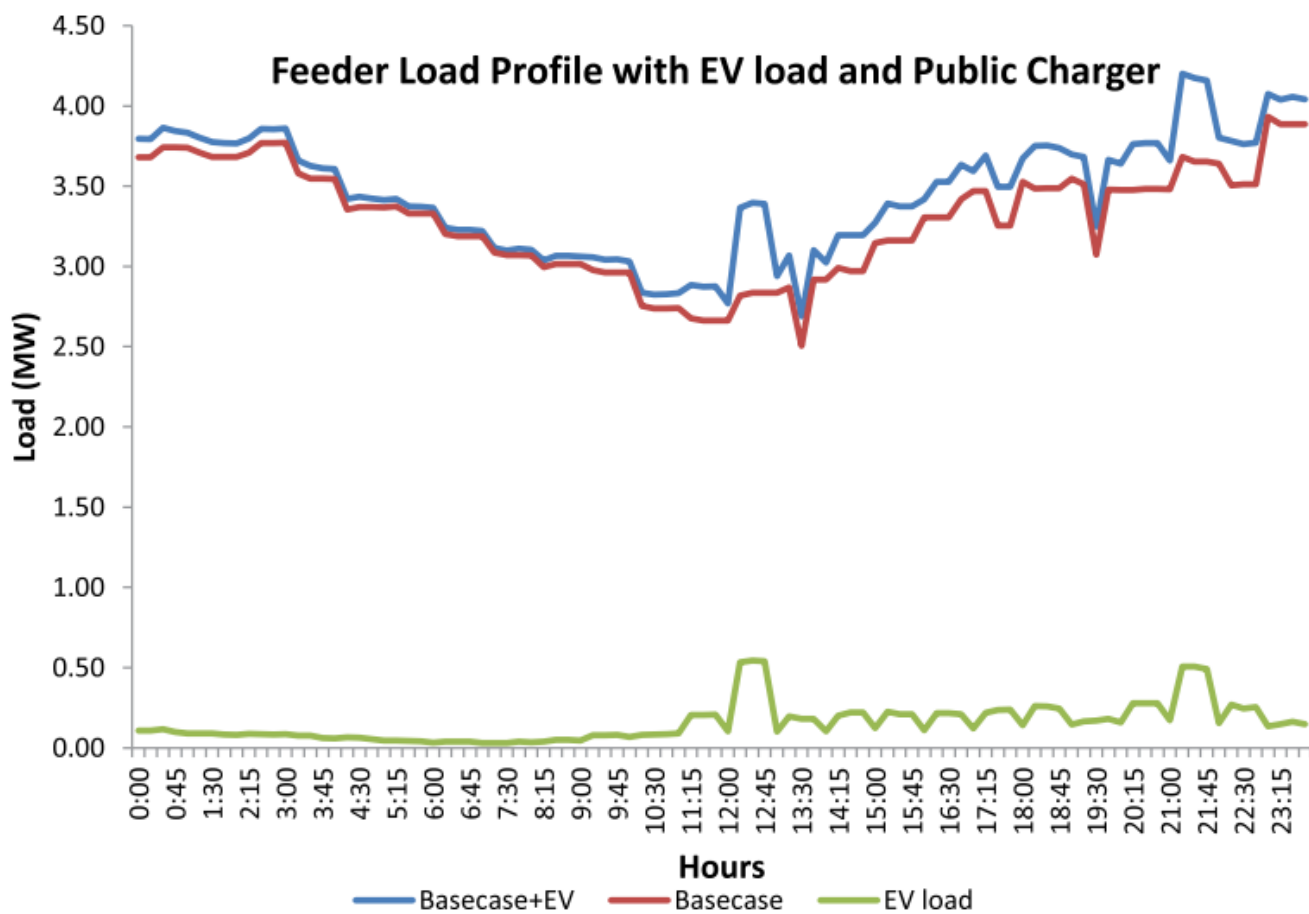
From the Distribution Companies' (DISCOMs) standpoint, concentrated demand from EV charging during peak periods can pose challenges. The heightened peak demand has the potential to strain electrical distribution systems, necessitating network upgrades that require substantial investment and prolonged implementation times. DISCOMs may acquire additional costly power to meet the load from EV charging; these investments in network upgrades can be avoided if a smart charging mechanism is developed.

A 2019 GIZ India report⁹ outlined the impact of incorporation of EVs into the feeder network in Delhi. The model depicts the current loading pattern of the feeder, incorporating the additional load introduced by the EV public charging station. The addition of public charging stations brings about distinct impacts on feeder loading. The feeder experiences a peak load of 4.2 MW at 21:15 hours, coinciding with an EV load of 506.65 kW as shown in **Figure 2**. Notably, the EV peak load of 543.96 kW occurs at 12:30 pm, contributing to 19.65% of the feeder load, which is 2.77 MW at that time. Over the course of the day, the feeder consumes a total of 82.96 MWh, with EV load accounting for 4.46% of total energy consumption. The feeder observes an energy loss of 2.69%, amounting to 2.23 MWh with EV load. Overall, these observations underscore the dynamic impact of EV charging on feeder loading, emphasizing the need for strategic planning and grid management to accommodate the evolving demands of electric mobility. Such impacts can be reduced by way of load balancing and smart charging.

⁸ Charging infrastructure for commercial electric vehicles: challenges and future works. IEEE Access 2021;9:121476e92. <https://doi.org/10.1109/ACCESS.2021.3108817>

⁹ Dr C. R. Atla et. al., 'Impact Assessment of Large-Scale Integration of Electric Vehicle Charging Infrastructure in the Electricity Distribution System', 2019

Figure 4: Feeder load profile with EV public charging2



1.2 The Indian Context and Freight Corridors

India needs to explore and adopt smart charging strategies more aggressively to optimize grid use, reduce costs, and integrate renewable energy sources into its power grid. Freight corridors, such as the **Delhi-Jaipur corridor**, are particularly important areas of study. These corridors experience high traffic density, and the large-scale introduction of EFVs can place significant stress on the power grid, potentially leading to grid capacity challenges and high upgrade costs if not managed properly.

Smart charging offers a sustainable solution by shifting the EV freight charging load to off-peak periods or times of high renewable energy availability, such as midday solar peaks. This approach reduces the need for immediate grid infrastructure upgrades while promoting renewable energy integration, ensuring both economic and environmental benefits.

Figure 5: Price based coordination method for smart charging

Real time pricing

- The real time price variation allows the charging cost minimization objective to be performed in a real charging scenario.

Time of use

- The time of use tariff is defined as the fixed price allotted to time slots. These prices are published on an actual day of operation so that the customer can schedule the operation of appliances to reduce the electricity cost by shifting the flexible loads to a low price period.

Critical peak pricing

- CPP works under the same TOU principle with the added difference that it is applied for a period of high demand. For applying CPP, days are categorised into critical days and non-critical days using various methods.

Peak time rebate

- The utility provides a rebate to the customer to limit consumption within a predefined limit. The economic effectiveness of the scheme is dependent on the predefined critical baseline load as it required development of precise baseline load.

Dynamic pricing

- To maintain generation – demand balance, demand response from the EV charging load is the preferred choice of system operator because of shiftable nature of EV charging load. Here electricity price is the only influencing parameter in performing demand response in a decentralized strategy.

Source: MP Ensystems Research, 2024

*In the Indian context **time of use (TOU)** pricing is a viable option and is emphasized for smart charging due to its effectiveness in **grid management**. It helps optimize energy costs by encouraging users to **charge during off-peak hours**, reducing strain on the grid during peak periods. This aligns with **driving patterns of freight vehicles**, allowing for a more balanced and sustainable use of the grid.*

This map illustrates the route of the Delhi to Jaipur Highway (NH48) through northern and central India. The highway is highlighted in red, starting from Delhi and passing through Gurugram, Rewari, Alwar, and ending in Jaipur. Four toll plazas are marked with red dots along the route: Kherki Daula, Shahjahanpur, Manoharpur, and Jaipur. The map also shows the boundaries of various districts, including Delhi, Gurugram, Rewari, Alwar, Jaipur, and others. A legend in the bottom right corner identifies the red line as the Delhi to Jaipur Highway (NH48) and the red dots as Toll Plaza. A scale bar indicates distances up to 20 km.

The Delhi-Jaipur corridor, an important freight route, presents unique challenges due to high traffic density and the growing demand for electric vehicle (EV) freight charging. The corridor's heavy use means that significant pressure is placed on the power grid, particularly with the anticipated increase in electric freight vehicles (EFVs). The study examines grid capacity, load profiles, and the potential for using Time-of-Day (ToD) pricing to shift charging demand to off-peak solar hours. The **Delhi-Jaipur corridor** is part of National Highway 48 (NH48), which extends from Delhi to Chennai over a total distance of 2807 km. The section from Kherki Toll Plaza in Gurugram to Daulatpura Toll Plaza near

Jaipur, covering the route between Delhi and Jaipur, takes approximately 5 hours and 45 minutes to travel. Along this route, there are 15 key cities and towns, including Delhi, Gurugram, Manesar, and Jaipur, which are strategically significant for initial site visits. Moreover, the corridor features **Industrial Model Townships (IMTs)** such as Manesar, Patwandi, Bawal, and Bhairra Industrial Estate, which play a crucial role in freight and logistics operations.

Some of the reasons for the importance of the Delhi-Jaipur corridor are in the figure below:

Figure 7: Importance of the Delhi-Jaipur corridor

Economic Significance

The Delhi-Jaipur corridor is a **major economic artery**, facilitating the movement of goods and services between two major cities. Economic activity depends on efficient transportation, and adding smart charging along this corridor can improve the logistics and freight operations' sustainability and efficacy

Traffic volume

This corridor experiences **high traffic volume**, especially in terms of freight movement. Understanding the **unique challenges and demands** associated with **heavy truck traffic** is essential for **planning and implementing effective smart charging** infrastructure.

Logistic hubs and IMTs

Both Delhi and Jaipur are **significant logistic hubs**, and the corridor plays a key role in supporting **supply chain activities** and have IMTs (Industrial Model Townships) **along the corridor**. Smart charging solutions can contribute to the **efficiency and sustainability** of freight transportation, reducing **operational costs** and environmental impact.

Technological showcase

The implementation of smart charging infrastructure along the Delhi-Jaipur corridor can serve as a **technological showcase for the integration of electric and smart transportation solutions**. Lessons learned from this corridor can potentially be applied to other **major transportation routes in the country**.

Government Initiatives

The Indian government has been actively promoting electric mobility and has set ambitious targets for the adoption of electric vehicles. Studying the Delhi-Jaipur corridor aligns with national initiatives, and insights gained from this study can inform policies and regulations related to smart charging and electric mobility.

Source: MP Ensystems Research, 2024

Indian Context | Grid integration challenges

The corridor's high traffic density poses challenges to the existing power grid infrastructure. Studying the integration of smart charging along this route involves addressing grid capacity issues, demand management, and grid resilience to support the growing electric vehicle ecosystem.

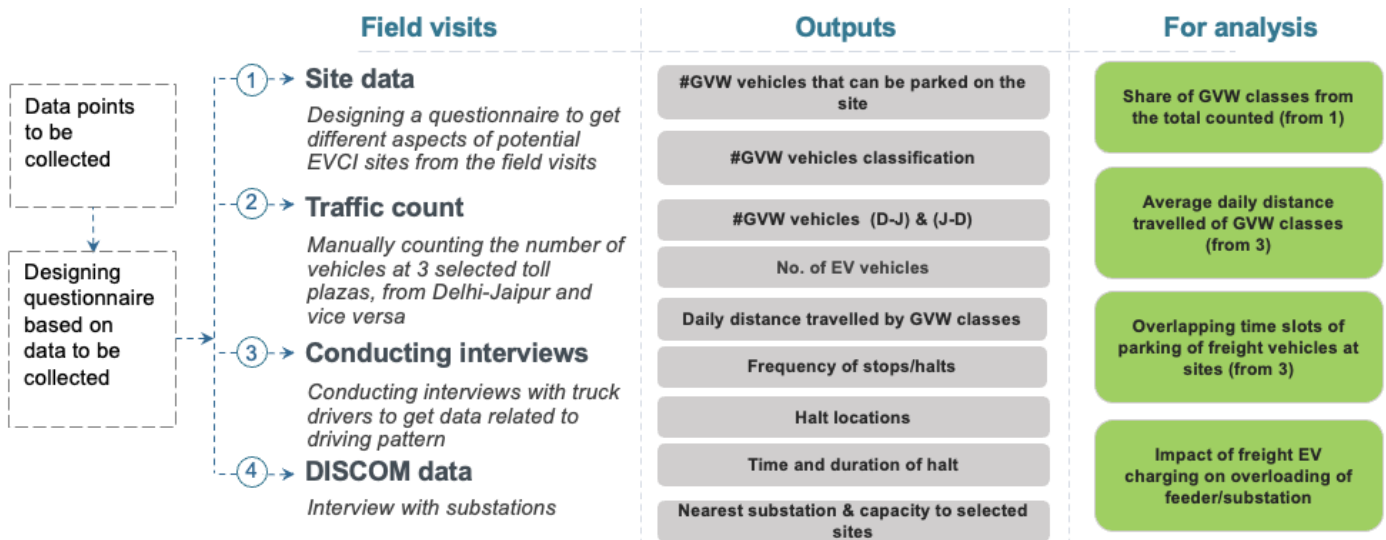
Site visit approach and study

Despite the high traffic volume along the corridor, limited analysis has been done to classify the types of vehicles, and their categorization. This study aims to bridge that gap through a detailed methodology, including surveys and field visits.

The surveys were designed to collect comprehensive data points, such as:

- **Daily distance travelled** by trucks based on Gross Vehicle Weight (GVW) classification.
- **Hourly truck volume** broken down by vehicle body type (rigid trucks or tractor-trailers) and GVW classes (7t to 12t, 12t to 16t, 16t to 25t, and >25t).
- **Fuel type, vehicle halts, and stoppage locations** along the corridor, as well as payload variability and the proportion of empty trips.

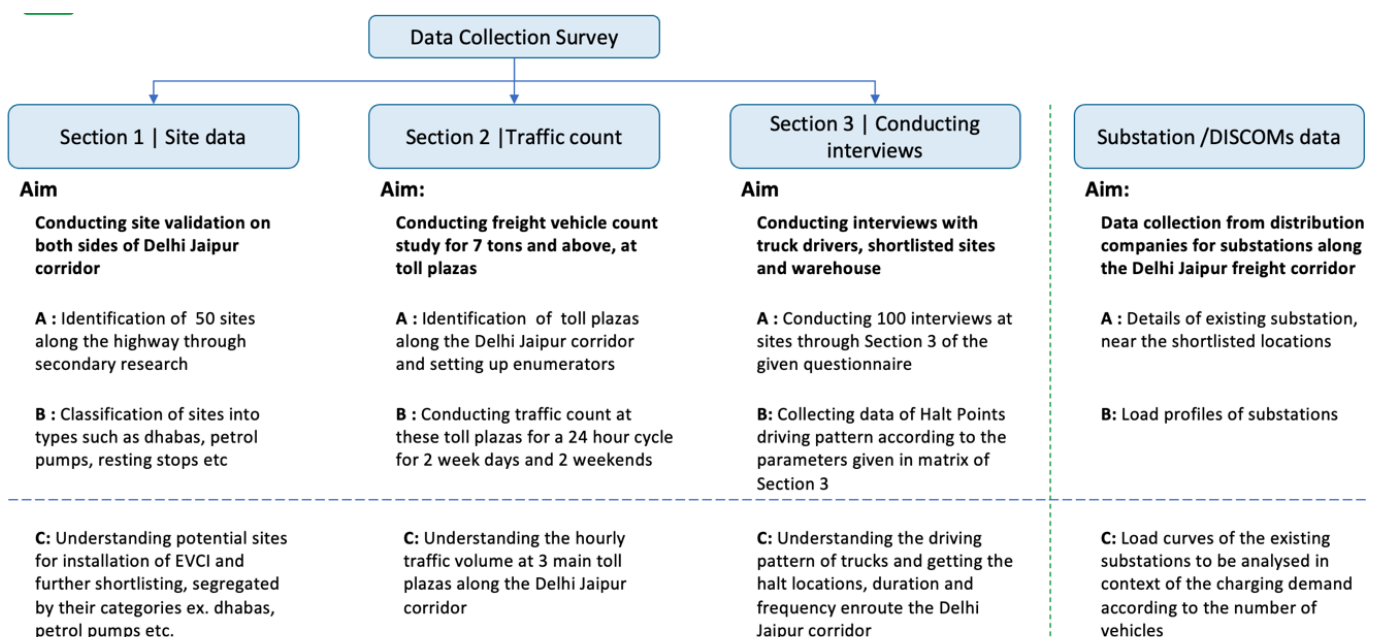
Figure 8: Delhi-Jaipur site analysis approach



Source: MP Ensystems Research, 2024

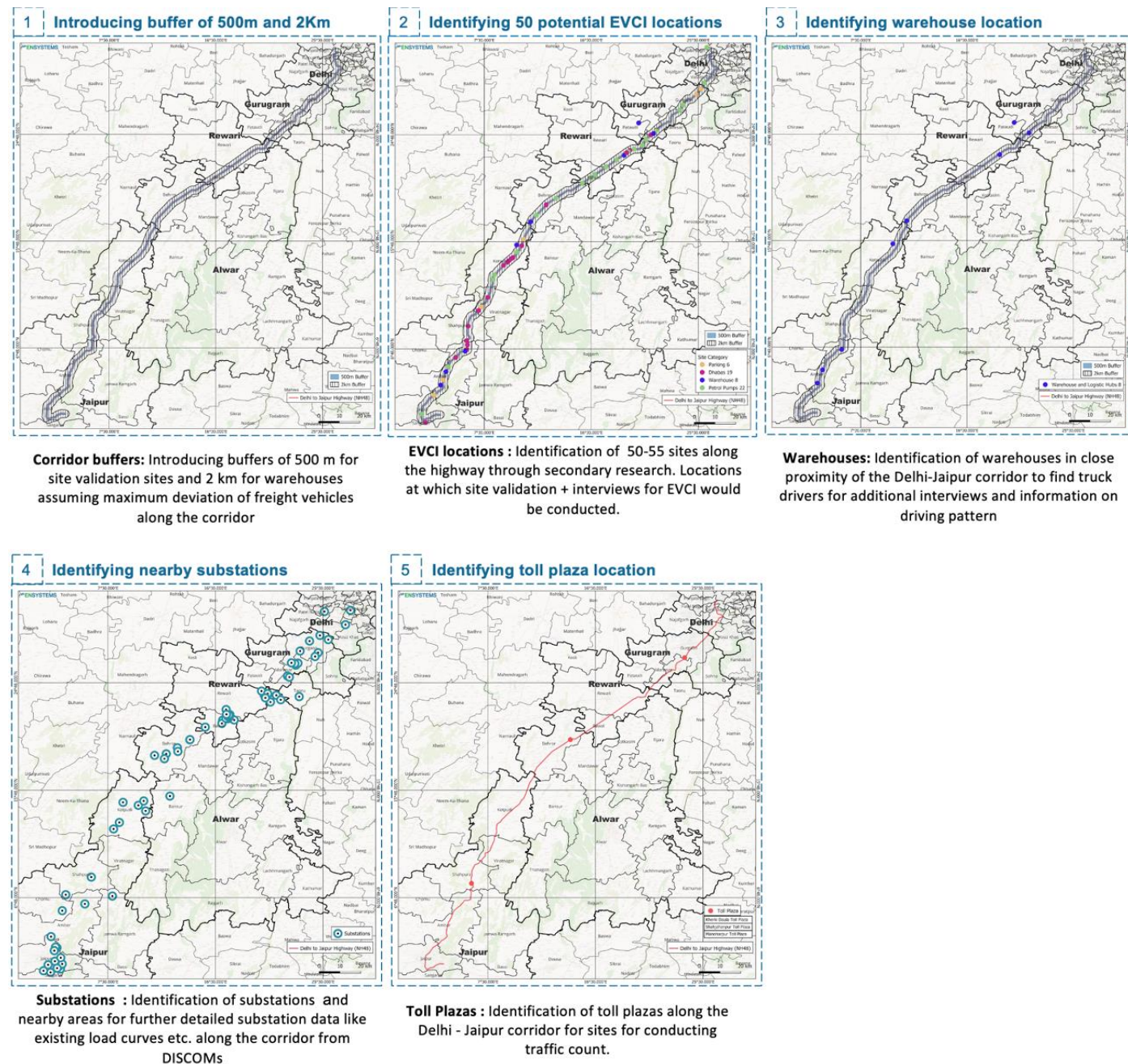
For on-ground site visit data collection, the study questionnaires were divided into three main sections to gain a comprehensive understanding of the Delhi-Jaipur corridor. These sections focused on gathering insights from site owners regarding location attributes, assessing the traffic volume along the corridor, and analysing individual driver patterns, behaviours, and stoppage trends. Visits were also conducted to nearby substations at several potential sites to evaluate the load curve for EVCI installation feasibility.

Figure 9: Detailed objectives from the site survey and data collection exercise



Source: MP Ensystems Research, 2024

Figure 10: Step wise approach for site classification, categorisation and shortlisting



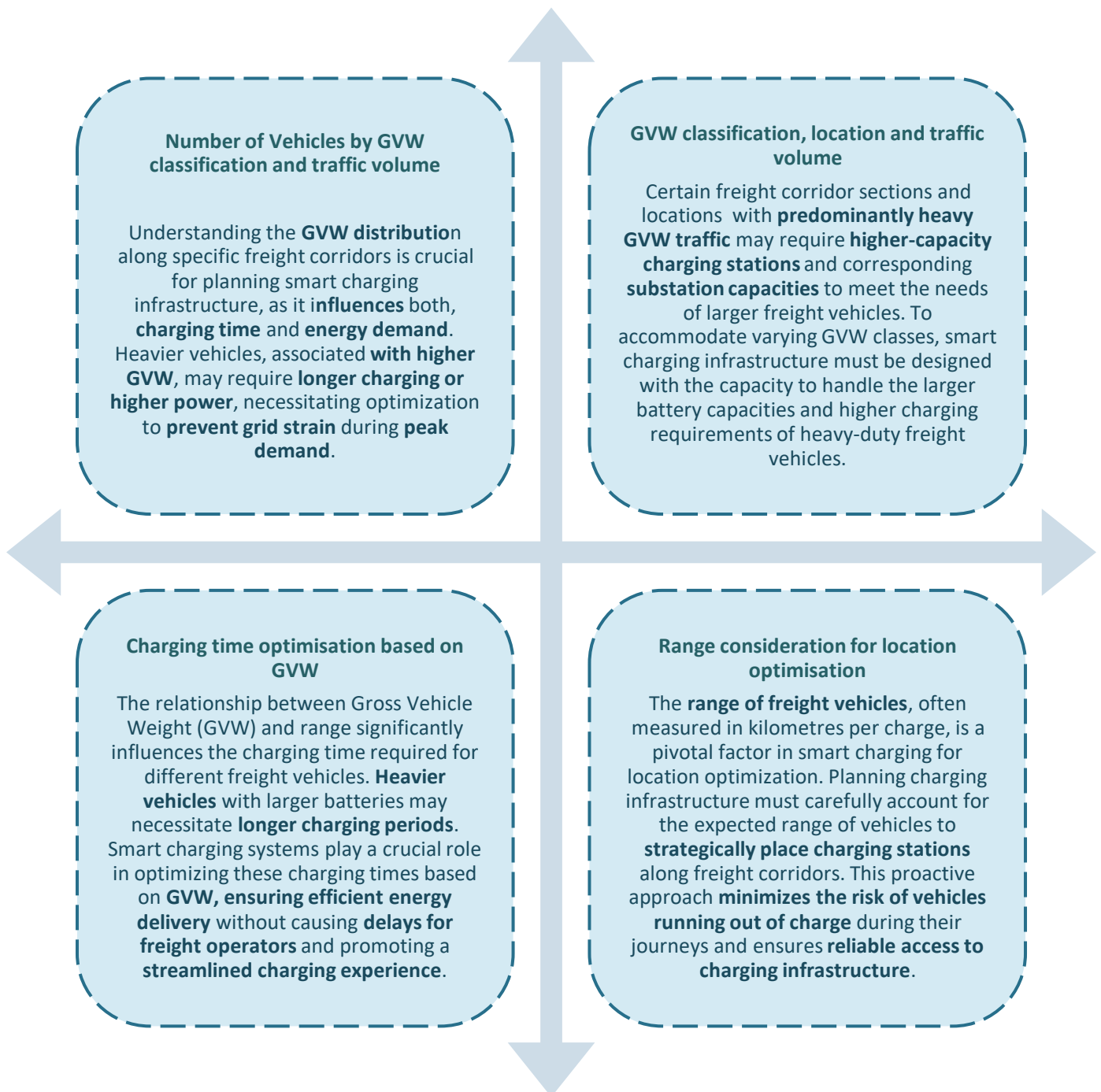
Source: MP Ensystems Research, 2024

Figure 11: Snapshot of the various substations visited



Source: MP Ensystems Research, 2024

Figure 12: Traffic count and GVW importance and relationship



Source: MP Ensystems Research, 2024

Section3: Interview questionnaires

Detailed questionnaires were also developed to understand the driver stoppage points, driver patterns their last location stoppage points etc. *Section 3 of the questionnaire delved into an extensive exercise of truck driver interviews on the sites shortlisted. With an initial sample size of 100+, the interviews helped us also understand the relation between the type of vehicle and the site itself.*

Figure 13: Truck driver survey: Data collection points and survey

Site locations Potential site locations capture and shortlisting									
Geographical location		Site/Area type		Truck parking capacity		Land ownership type			
Available area		Area designated to charging station		Rules for freight vehicles		Willingness to invest			
Parking profile			Accessibility			Charging stations			
Vehicles parked on the location and their classification			Site access from major highways			Charging station in the area		Transformer location nearby	
Share of freight vehicles		Average time and duration		Location from the highway		Any challenges in access		Charging station type	
								Charging station load	

Name of the Driver			Organization			Fleet size of Organization.			
Employee type: Contractual Freelance Full time			Phone no.(Optional)			Name of the city transporting goods to :			
Name of current halt location:			Area:			Date(dd/mm/yy)			
Start point of trip Location name:			End Point of trip Location Name			Time of Interview			
1) Journey Details	2) Type of Vehicle(ton)	3) Latitude and longitude (of the location)	4) Halt Location Type(Current)	5) Time and Duration of Halt (eg 4am to 5am)	6) How frequent is this trip made in 24 hrs	7) How frequent is this trip made in a week	8) Journey Duration (eg 5hrs 15 mins from start to end)	9) Type of load being carried	10) Payload carried (in tons)
☐ Delhi-Jaipur ☐ Jaipur Delhi ☐ Other _____	☐ 3-7 ☐ 7-12 ☐ 12-16 ☐ 16-25 ☐ >25		☐ Dhabha ☐ Petrol pump ☐ Logistic hub ☐ General open space ☐ Other _____		☐ Once ☐ Twice ☐ Thrice	☐ Once ☐ Twice ☐ Thrice ☐ 4 times ☐ 5 times ☐ 6 times ☐ Everyday		☐ Agricultural ☐ Commercial ☐ Industrial	
11) How frequently do you stop at this location in a week?	12) How Frequent do you stop at this location in a day?	13) Name of the previous halt location	14) Type of the previous halt location	15) Distance of the previous halt location from current	16) No. of Empty load trips in a day	17) No. of Empty load trips in a week	18) What is name of first location you halt at since start point	19) Distance of the first halt location since start	20) Average daily distance travelled (Delhi to Jaipur to and fro)
☐ 1 time ☐ 2 times ☐ 3 times ☐ 4 times ☐ 5 times ☐ 6 times ☐ 7 times	☐ 1 time ☐ 2 times ☐ 3 times ☐ 4 times		☐ Dhabha ☐ Petrol pump ☐ Logistic hub ☐ General open space ☐ Other _____						
21) Does the truck have Ac Or Non-Ac cabin	22) Is the whole truck refrigerated?	23) How often in an week do you travel through the Delhi Jaipur corridor?		24) Name of other locations or stops within Delhi to Jaipur where the driver stops ?		25) How many days of which months are you on call/on the road for delivery?		26) Is there a difference in the types of cargos at specific parts of the year? If yes, can you please mention the reason? Ans:	
☐ Ac Cabin ☐ Non Ac Cabin	☐ Yes ☐ No	☐ Once ☐ Twice ☐ Thrice ☐ 4 times ☐ 5times ☐ 6 times ☐ 7 times							

Source: MP Ensystems Research, 2024

These surveys were conducted across both corridor directions on two weekdays and a weekend, primarily at toll plazas. To identify potential electric vehicle charging infrastructure (EVCI) sites, a buffer zone of 500 meters on both sides of the highway and 2 kilometers around warehouses was created, mapping 50-55 potential sites. These sites

included dhabas, petrol pumps, and parking plots. Interviews with warehouse managers were conducted to gain insights into driver behaviour, while nearby substations were also mapped and assessed.

To identify and shortlist potential sites for electric vehicle charging infrastructure (EVCI) along the Delhi-Jaipur corridor, a detailed site assessment was conducted based on several key parameters:

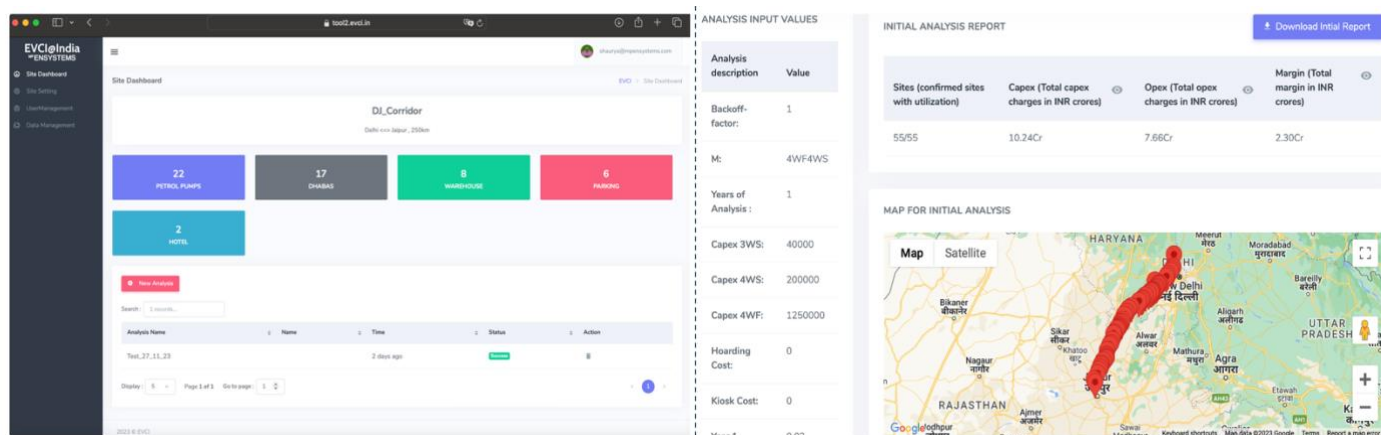
- **Potential Site location capture and shortlisting:** The initial step involved mapping potential locations along the corridor based on their **geographical location** and the specific **site/area type**, such as open parking lots, petrol stations, or dhabas. Sites were assessed for their **truck parking capacity** to ensure that they could accommodate the high volume of freight vehicles, with further consideration of **land ownership type**—whether the land was privately owned, government-owned, or leased—which impacts the feasibility of setting up charging stations.
- **Parking profile:** The next step in site assessment involved analyzing the **parking profile** of these locations. This included a detailed classification of the vehicles typically parked at these sites, focusing on the **share of freight vehicles** and the **average time and duration** these vehicles remained parked. Understanding how long freight vehicles stayed at a location is crucial for determining the viability of installing fast-charging stations, as the time vehicles remain idle influences charging patterns and infrastructure needs.
- **Accessibility:** Another important criterion was the **accessibility** of the site from major highways. Sites were evaluated based on their proximity to the corridor, ensuring ease of access for freight vehicles traveling along the route. **Location from the highway and ease of access** were critical factors in the selection process, as highly accessible sites would experience more frequent use and contribute to the efficiency of freight operations.
- **Charging stations:** A critical factor in site evaluation was the presence of nearby **transformers** and existing **charging infrastructure**. Sites were assessed for their **proximity to transformers** and whether they had suitable electrical capacity to support EV charging stations. In addition, the presence of **charging stations in the area** was documented, including details on the **type of charging stations** (e.g., fast or ultra-fast) and their **load capacity**. These factors are essential in determining the ease of integrating new charging points and whether existing infrastructure could support additional EV charging demands.

The questionnaires were designed to extensively gather both qualitative data and quantitative data to get a better and more detailed picture of the freight movement across the Delhi - Jaipur corridor

By considering all these aspects—geographical location, parking profile, accessibility, and the presence of transformers and existing charging stations—a shortlist of potential EVCI sites was created to support the deployment of EVCI and understand the potential for smart charging along the Delhi-Jaipur corridor.

The data collected was run through freight tool developed by MP Ensystems used for identification of locations. These location were then followed by a detailed site validation study to understand each side and parameters for installation of chargers and possible utilisation of chargers.

Figure 14: EVCI tool analysis for the Delhi-Jaipur corridor



Source: MP Ensystems Research, 2024

Detailed **site validations** along the Delhi-Jaipur corridor, visit to the nearby substations and understanding the peak load hours and capacity of the substations

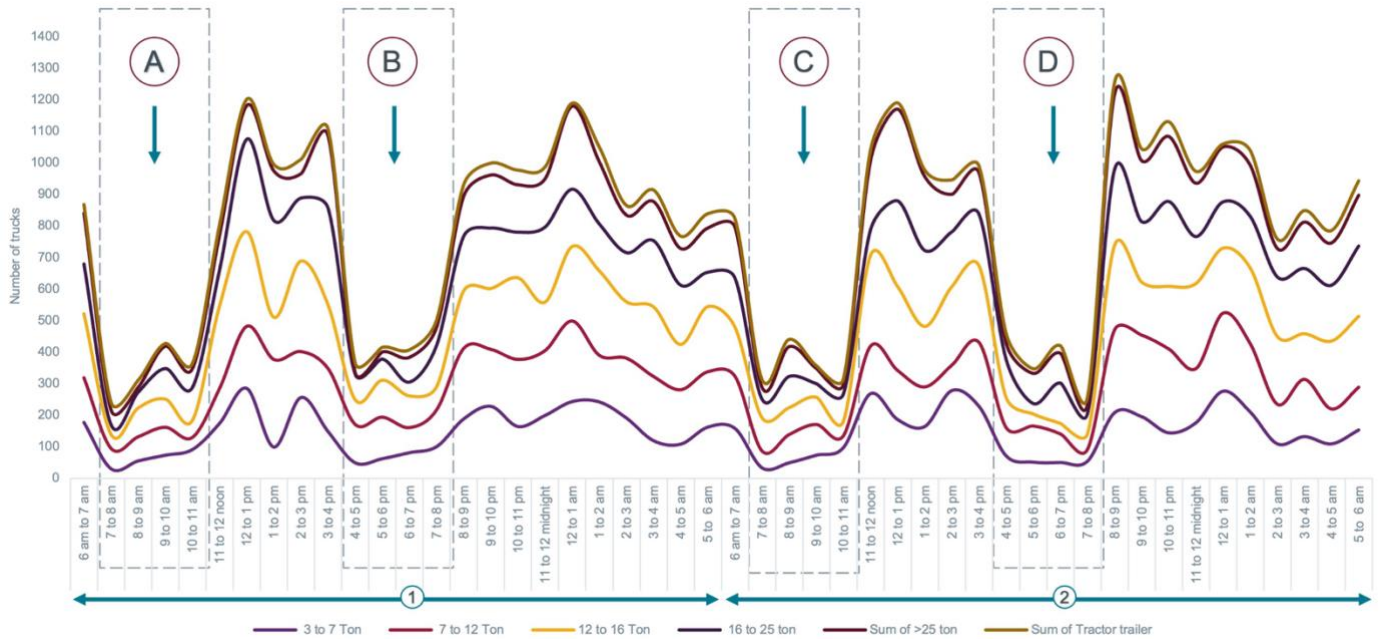
Figure 15: Site validation snapshot



Source: MP Ensystems Research, 2024

Slots and Delhi entry exit timings explanation/relation: Two main time slots for trucks entering Delhi: 11 PM to 7 AM and 11 AM to 4 PM. Trucks from different states parked in Transport Nagar during these slots. Evening time slot (Slot 2) sees increased incoming trucks and parking. Slots A (7am to 11am) and B (4pm to 8:00 pm) on day 1 and c and d on day 2 in the graph indicate a drop in the vehicle movement at the toll plazas indicating the vehicles being parked somewhere in the slots.

Figure 16: Example of (2-day) data on findings from traffic count survey across 3 toll plazas on weekdays and weekends



Source: MP Ensystems Research, 2024

From the study we were able to draw initial insights on key factors for successful freight vehicle charging implementation, which include emphasizing the influence of truck drivers' behaviour and movement patterns.

The study underscores the need for adequate charging infrastructure during daylight hours and proposes exploration of wind power as a night-time energy source. Smart charging strategies must account for drivers' discretionary stoppages. Insights also include the importance of solar PV integration for cost reduction, the role of smart tariffs in sharing benefits, and the relatively minor impact of EV charging on the grid in the current scenario. ToD pricing can manage EV demand effectively, with a focus on aligning charging with solar availability and accommodating diverse stopping patterns. Overall, integrating renewable energy sources with DISCOMs and addressing driver behaviour are crucial for sustainable freight transportation.

From the study one of our greatest understanding was the detailed and granular data that we were able to capture and the potential it carries in understanding the various aspects that come into play when we are talking about investing and working on such an extensive infrastructure. The table below summarises some of our key findings.

Table 2: General Observations during preliminary site visit conducted along the Delhi-Jaipur corridor

Parameter		Observations
1	Stoppage patterns	Random stoppages in areas dependent on drivers. The average duration of stoppage was found to be between 30 minutes to 1 hour , and these stoppages are at the complete discretion of the driver, depending on the final destination of the goods being delivered
2	Share of segments	No Electric trucks of any categories were found during the exercise
3	Traffic count	2 distinct patterns were observed during the day from the traffic count data – in the weekday and weekends according to the entry and exit timings
4	Driver schedule, patterns and discussion with logistic companies	Since truck drivers have significant discretion in decision-making, their behaviour, driving patterns, and the movement of freight vehicles—including routes taken, rest stops, and the duration of stops during solar hours—is influenced by the requirements of the delivery time of goods and government regulations on freight driving hours of particular state or city
5	Warehouses	The warehouses visited are only equipped with spaces available for loading and unloading of the goods with operational timings between 9:00 am to 6:00 pm.

Source: MP Ensystems Research, 2024

Chapter 2: Case Studies in smart charging global scenario and the Indian context

2.1 The Global Context | Impact of ToD/ToU pricing on EV charging

This chapter is structured into 2 primary sections. The first section delves into three case studies, then subsequently moves to providing a comprehensive understanding of ToD/ToU strategies in the Indian context. This will serve as a foundation for comprehending the ToD/ToU pricing in the Indian context.

Three case studies: Through the analysis of various case studies, we have examined the impact of ToD pricing on EV charging. These studies have shed light on how ToD tariff structures effectively facilitate the charging of EVs.

Introduction to ToD, smart charging and RE Integration concepts in the Indian context: The aim of this subsection is to understand RE integration and implementing ToD pricing methods within the Indian context, particularly focusing on EV charging infrastructure. By diverging from traditional approaches and emphasizing the importance of smart charging based on price triggers alongside exploring ToD structures, the aim is to come up with ways to understand grid impact, reduce reliance on non-renewable energy sources, and ensure sustainability and resilience in the energy distribution system.

2.2 Case studies

Case study 1: Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management¹⁰

Objective: The study focuses on quantifying the value of managed charging in high RE and EV adoption scenario in California.

Methodology: Three charging scenarios are considered in this study as described below:

- Unmanaged Charging: Plug in EV (PEV) starts charging immediately after plugged in.
- Smart Charging: PEVs are plugged in at the same times as unmanaged charging, but charging can be controlled within plugged in periods to achieve the charging requirement.
- Overnight Time-of-Use¹¹ Charging: Smart charging strategy in which charging only start during off-peak hours (e.g., 10 pm to 2 am) to benefit from lower ToU rates.

Integrated approach is used for simulation which has two parts

- Vehicle charging behaviour simulation
- Economic power dispatch simulation as follows:
 - BEAM: agent-based PEV mobility and charging model is used for simulating charging behaviour of PEVs.
 - PLEXOS: power sector dispatch model is used for unit commitment and economic dispatch simulation

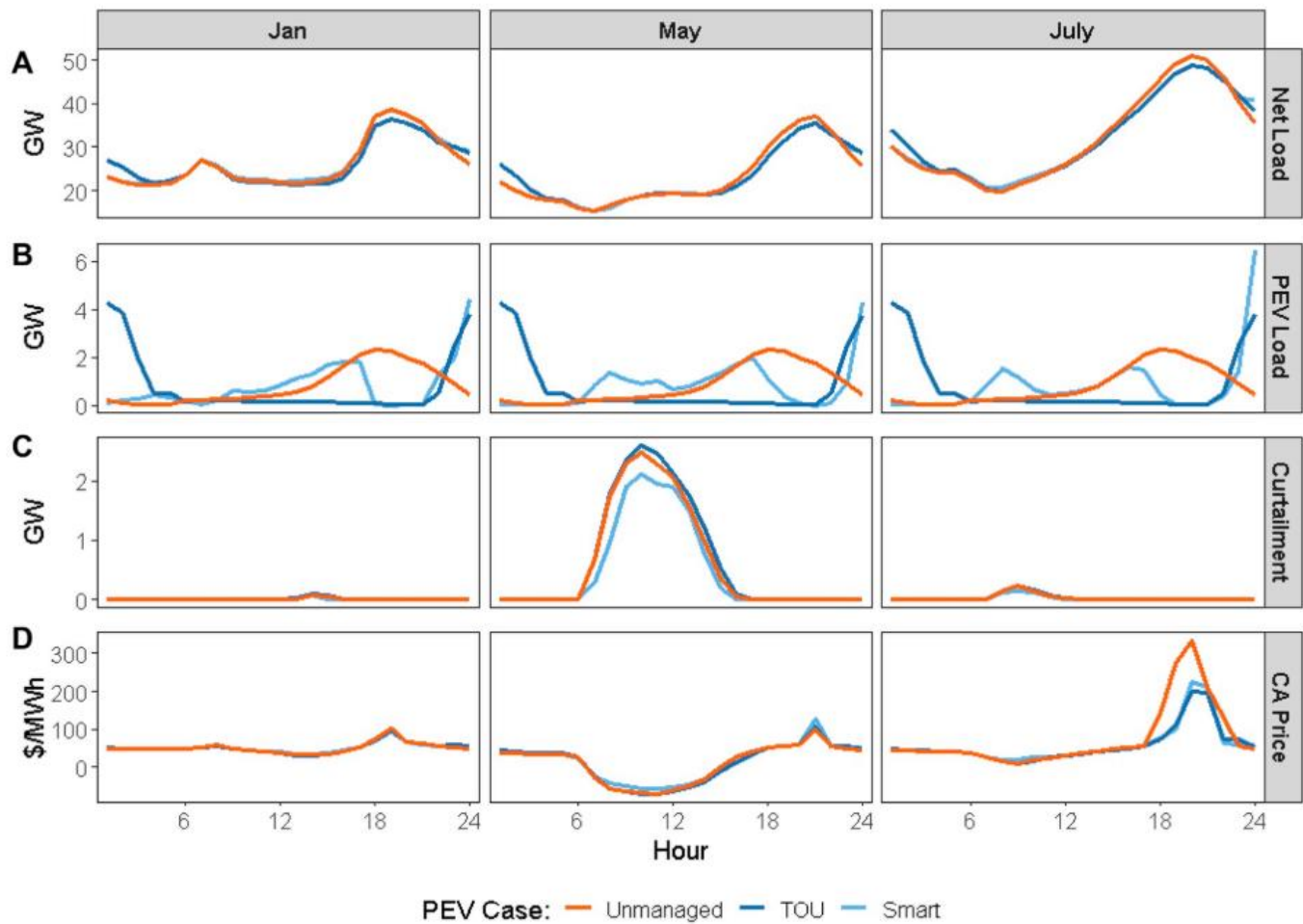
Output:

¹⁰ Julia K. Szinai, Colin J.R. Sheppard, Nikit Abhyankar, Anand R. Gopal, Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management, Energy Policy, Volume 136, 2020

¹¹ ToU and ToD terms are interchangeable- the case study here has referred to Time of Use. In the rest of the report, we refer to ToD.

Figure 17 below shows the impact of EV charging on net load, RE curtailment and utility average cost in three scenarios.

Figure 17: (A) "Net Load" is California system load net of solar PV, solar thermal and wind generation; (B) "PEV Load" shows Unmanaged, TOU, and smart charging PEV loads; (C) "Curtailment" is curtailment of California solar PV, solar thermal, and wind generation; D) "CA Price" is the Load-weighted average price of California utility regions



Unmanaged charging leads to higher peak demand times. ToU charging, concentrates the charging at night and avoids peak hours but does not help in renewable energy curtailment. Smart charging achieves both goals as it utilizes renewable power during the day and then charges at lower night rates, reducing both costs and strain on the grid.

Figure 18: Annual California total system cost. Annual total system cost for California includes the grid operating cost from generation, emissions, and net imports.

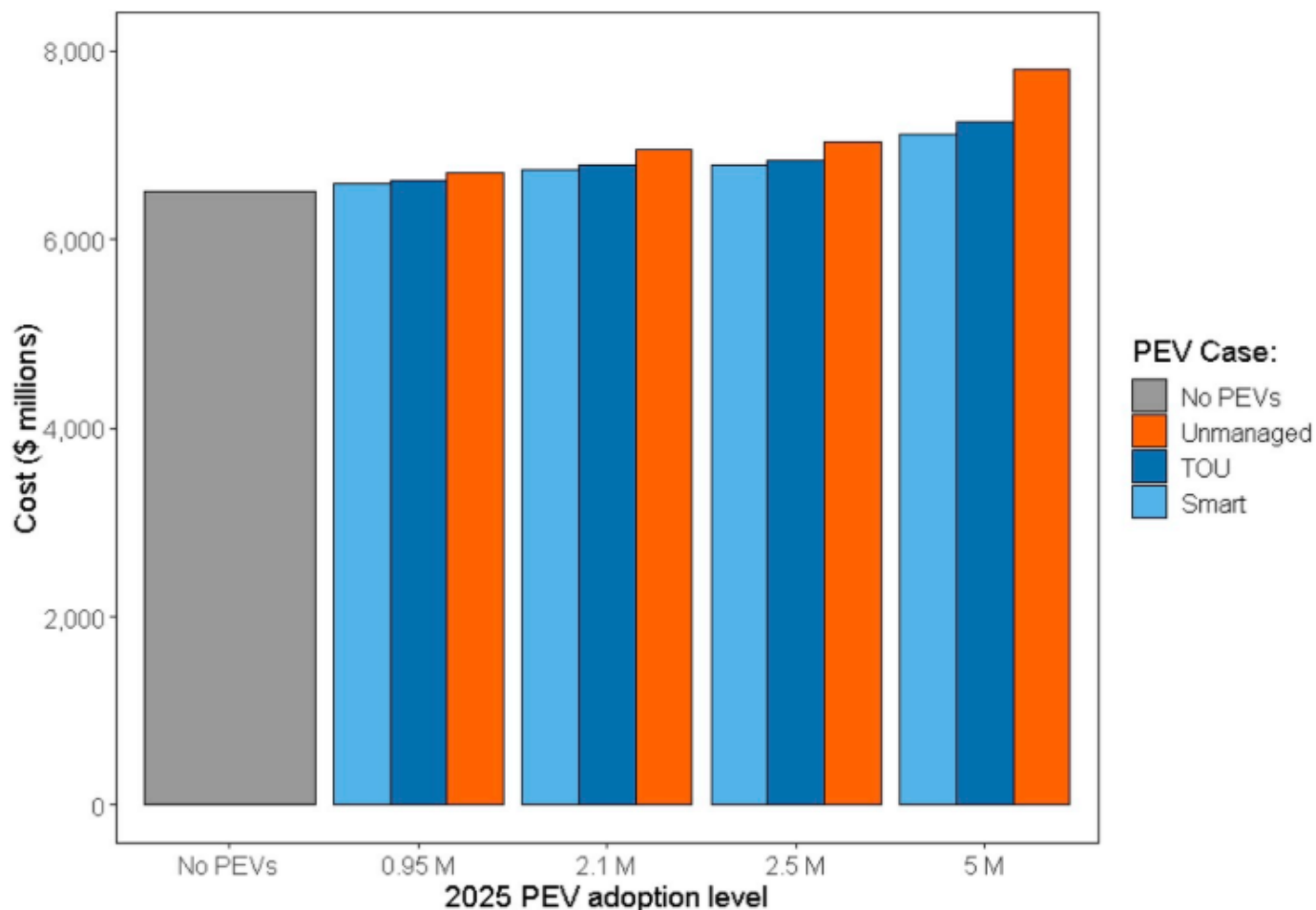


Figure 18 shows the system cost for three charging scenarios for EV adoption level up to no PEVs to 5M PEVs in 2025 in California. Introducing PEVs to the grid in California results in overall rise in annual total system costs across all scenarios due to additional generation required to meet EV charging load demands. However, managed charging strategy significantly influences the extent of this cost escalation. Smart charging results in lower system costs compared to unmanaged charging across different levels of PEV adoption. This is attributed to reduced peak loads, allowing for the utilization of less expensive RE generators. Similarly, ToU charging reduces system costs relative to unmanaged charging by lessening load in peak loading period, which help decreasing ramping needs primarily from expensive natural gas generation.

Conclusion:

For transportation electrification and grid decarbonization, hybrid smart charging and ToU strategies can be implemented to mitigate higher grid operating costs, RE curtailment.

Case study 2: EV charging pattern with Time of Use rates in California and Portland¹²

Objective: Analyse the charging patterns of PEVs under basic and ToU rates using EV charging profile data collected from service territories in California state and around Portland city.

Methodology: The data used in this study comprises of hourly average charging profiles of EVs under various pricing schemes for two distinct utilities: Portland General Electric (PGE) and Pacific Gas and Electric (PG&E). The ToU rate for PGE and PG&E are shown in **Figure 19** and **Figure 20** respectively.

Figure 19: Portland General Electric ToU off-peak, mid-peak, and on-peak schedules and associated prices for weekdays, Saturday, and Sunday.

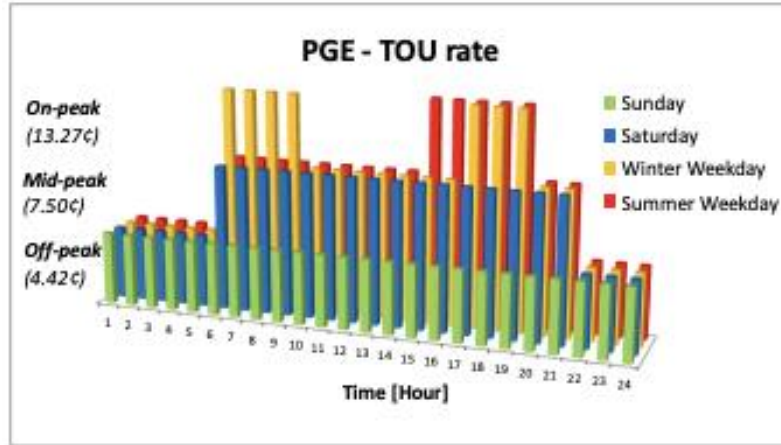
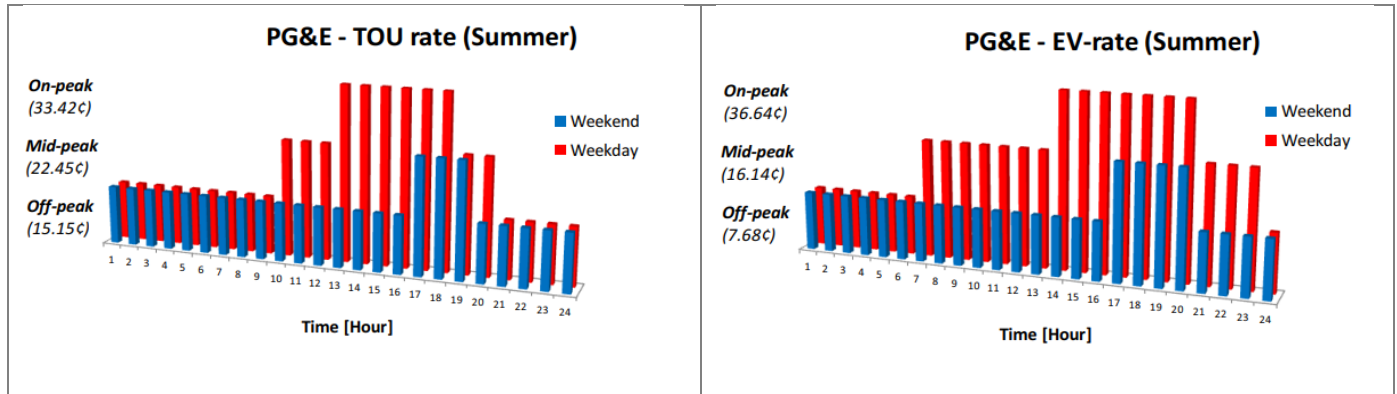


Figure 20: PG & E (A) ToU rates (E-6) and (B) EV-rate (E-9A) and associated off-peak, mid-peak, and on-peak times and prices for summer weekdays and weekends



(A)

(B)

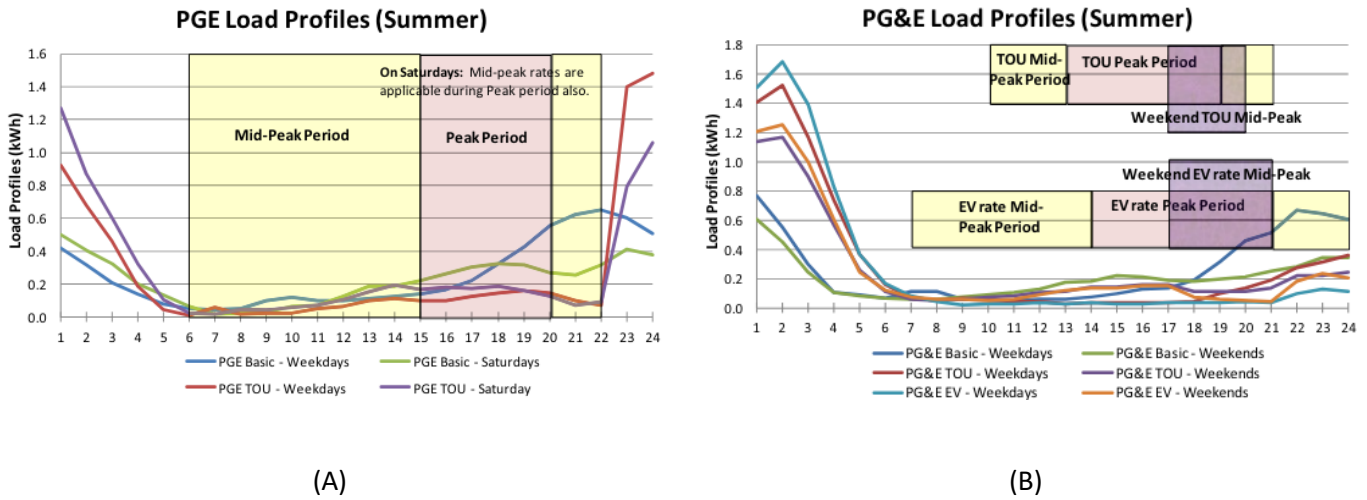
Output:

Figure 21(A) shows the daily EV charging load profiles for 24 hours for PGE customer groups during the summer months, peak and off peak periods are also marked in the figure. The charging demand in peak period is reduced and subsequently increased in off peak period. This implies that ToU customers shows a more intentional effort to avoid the higher-priced evening charging peak compared to the group with basic rate, which maintains constant prices. Furthermore, the charging patterns of the group with ToU rates on weekends exhibit a similar trend to weekdays,

¹² M. Biviji, C. Uçkun, G. Bassett, J. Wang and D. Ton, "Patterns of electric vehicle charging with time of use rates: Case studies in California and Portland," ISGT 2014, Washington, DC, USA, 2014

despite the absence of a penalty for peak loads. This suggests that customers stick to weekday off-peak period charging habits during weekends, irrespective of the relaxed ToU schedule for weekends.

Figure 21: EV charging load profile for basic tariff and ToD tariff (A) PGE (B) PG & E



In **Figure 21 (B)**, load profiles for the three PG&E customer groups are displayed for both weekdays and weekends. Like PGE customers, PG&E ToU and special EV-rate customers mostly charge their EVs during off-peak periods. Additionally, PG&E customers avoid charging during peak and mid-peak periods, continuing similar charging patterns on weekends irrespective of the different weekend rate structure.

Conclusion:

- This flexibility from EV charging can help utilities to manage EV charging loads using ToU pricing structures.
- ToU rate structure resulted in shifting of EV charging demand from peak period to off peak periods.

Case study 3: Powered up - Charging EVs without stressing the electricity network¹³

Electric Nation conducted a comprehensive smart charging trial spanning from January 2017 to December 2018, involving 673 PEV drivers recruited from the WPD (Western Power Distribution) region.

Objective: Electric Nation aimed to analyse the impact of various energy tariffs on drivers charging habits, especially during peak hours after the evening rush, notably in winter to reduce strain on substations.

Methodology: This trial was structured into three distinctive phases, each simulating potential future scenarios for managing electricity demand.

Smart chargers for the trial were sourced from Alfen and eVolt, both prominent players in smart charging technology. GreenFlux and CrowdCharge provided the back-office systems responsible for managing power delivery and receiving instructions from drivers. The trial participants were roughly evenly distributed between the two back-office suppliers.

- During Trial 1, also called a blind trial, participants experienced limited charging during periods of high electricity demand, the charging preference was given to EV owners with lower charger capacity and EV owners who mostly charge their EVs in off peak period. However, the trial was blind so the users were unaware of when their charging was restricted.
- Trial 2 introduced a more interactive approach through phone apps. CrowdCharge users can input their current state of charge and required charge and time period, ensuring sufficient power for their needs, while GreenFlux users could opt out of management for a 'high priority' charge in case of immediate charging requirement.
- In Trial 3, incentives were introduced to encourage off-peak charging, featuring a Time of Use tariff (ToU) where users could earn shopping vouchers for charging outside peak hours as shown in figure 6. CrowdCharge aimed to utilize the cheapest available energy by prioritizing charging based on need or off-peak rates. Meanwhile, GreenFlux allowed users to prioritize time or cost, which can be updated daily. Users can also opt out from managed charging during demand management.

Figure 22: Electric nation charging tariff

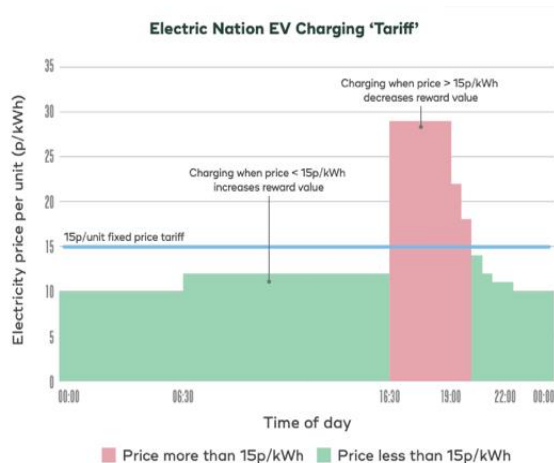
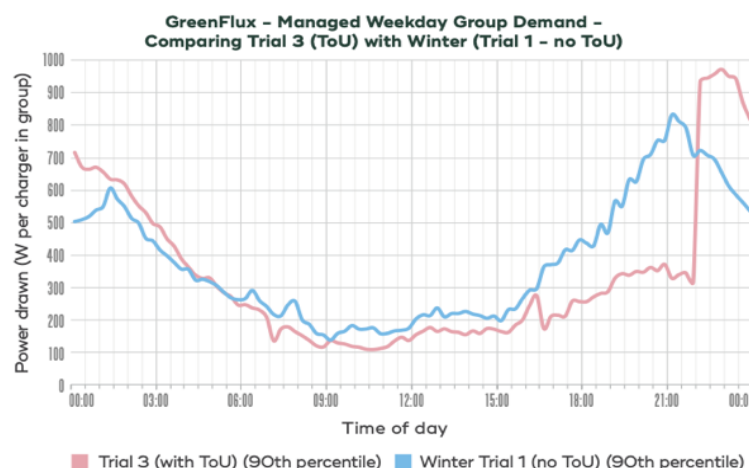


Figure 23: GreenFlux - Managed weekday group demand comparison for trial 1 and trial 3



Output: Cost optimization with GreenFlux leads to a sharp increase in demand at 10:00 pm in trial 3, as shown in Figure 23. Most of the participants who had delayed charging until after the peak tariff started charging simultaneously

¹³ The electric nation vehicle to grid project - [Electric-Nation-Powered-Up-Report-WEB.pdf \(electricnation.org.uk\)](https://electricnation.org.uk/Electric-Nation-Powered-Up-Report-WEB.pdf)

after end of peak period. This surge was notably more abrupt compared to the typical end of peak traffic period demand rise, which usually occurs gradually over several hours as drivers return home. Moreover, the surge peaked higher than in any previous trials. Fortunately, the 10:00 PM peak did not exceed the substation capacity, as the usual evening peak had passed.

The CrowdCharge algorithm for Trial 3 underwent an update, incorporating journey plans alongside the tariff to optimize charging during inexpensive periods whenever feasible. For instance, if a vehicle was plugged in at 18:00 pm with the next planned journey scheduled for the following morning but due to low level of interaction between participants and the journey planner, charging frequently took place during peak hours, resulting in minimal impact on peak demand by the system.

Conclusion:

ToU incentives effectively shift demand away from evening peaks, especially when supported by smart charging with user-friendly apps.

Key takeaways from case studies

Hybrid smart charging and ToU strategies offer effective solutions for transportation electrification and grid decarbonization. They can mitigate increased grid operating costs and reduce renewable energy curtailment. By leveraging the flexibility of EV charging, utilities can better manage charging loads through ToU pricing models. ToU incentives, particularly when paired with user-friendly smart charging apps, effectively encourage shifting demand away from evening peaks.

2.3 ToD smart charging and RE integration in the Indian context

Our strategy and approach for the study of charging in the Indian context differs from the general smart charging definitions¹⁴. We are of the opinion that implementing smart charging based on price triggers¹⁵ can be beneficial. India has not yet seen aggressive implementations of price triggers like ToD specifically for EV charging loads, so at present, it is a great opportunity to explore and assess both managed charging and ToD approaches for EV charging.

In the Indian context, ToD pricing can be a viable option and can be emphasized for smart charging due to its effectiveness in grid management. It helps optimize energy costs by encouraging users to charge during off-peak hours, reducing strain on the grid during peak periods. If driving patterns of freight vehicles can be adjusted as guided by these dynamic price signals, this can help lower whole system energy costs.

A pilot program in a controlled environment with smart charging to test out ToD structures can be a great case study to assess the feasibility and establish proof of concept. Exploring the integration of RE alongside ToD pricing strategies can be a viable approach. All DISCOMs are obligated to meet Renewable Purchase Obligations (RPOs)¹⁶, necessitating increased integration of RE into the grid. This integration involves the implementation of storage infrastructure and aligning demand with RE generation. By considering this option, EV charging demand can be shifted to effectively, absorb more renewable energy into the system at lower costs minimising need for storage capacity¹⁷.

¹⁴ Case where chargers actively control the power

¹⁵ Meaning trying to shift the charging demand to certain periods beneficial to the utility companies or DISCOMs

¹⁶ Renewable Purchase Obligation (RPO) mandates that all electricity distribution licensees should purchase or produce a minimum specified quantity of their requirements from Renewable Energy Sources. This is as per the Indian Electricity Act, 2003

¹⁷ Here the assumption is: aligning demand in RE generation period is least cost option as compared to integrating storage infrastructure for managing higher RE

By managing EV charging demand in tandem with RE availability, in theory we can encourage RE absorption into the grid, thus optimizing energy utilization. Solar hours, delineating periods of significant solar irradiance for energy generation, present an opportunity for optimization through detailed ToD pricing structures. These hours, varying by location, season, and weather, necessitate nuanced pricing to incentivize consumption alignment with peak solar generation.

Lower electricity rates during peak solar hours encourage consumers to utilize electricity-intensive activities, thereby reducing reliance on non-renewable energy sources during high-demand periods. Granular ToD pricing promotes even distribution of electricity demand throughout the day, alleviating strain on the grid during peak times and enhancing overall stability and efficiency. Conversely, higher pricing during non-solar hours incentivizes energy conservation and discourages unnecessary consumption, reinforcing sustainability objectives.

2.3.1 Understanding RE and ToD in the Indian context

The figure below presents key insights obtained from an additional literature review conducted to gain insights into the integration of renewable energy to DISCOMs in India, specifically focusing on time of day and time of use pricing. The points below provide valuable insights for understanding the Indian context of RE, DISCOMs and ToD methods.

Figure 24: Use of RE in the Indian context



Source: MP Ensystems Research, 2024

Given below are some general benefits to consumers and DISCOMs from RE (solar).

Table 3: Benefits for consumers and utilities for RE (solar) integration

Benefits to consumers from solar energy integration	
Cost savings	Solar energy integration often leads to lower electricity costs for consumers, especially during daylight hours. With net metering or feed-in tariffs, consumers may even generate excess energy during sunny periods, earning credits or receiving payments.
Energy independence	Solar panels on rooftops empower consumers to generate their own electricity, reducing dependency on the grid. This independence is especially valuable during power outages or in areas with unreliable grid access.
Environmental consciousness	Consumers benefit from using a clean and sustainable energy source, contributing to reduced carbon emissions and environmental preservation. This aligns with the growing trend of environmentally conscious consumer choices.
Grid reliability	Solar energy can enhance grid reliability as decentralized solar installations reduce the burden on the central grid during peak hours. Consumers experience more stable electricity supply, particularly in regions prone to power shortages.
Government incentives	Consumers often enjoy government incentives and subsidies for adopting solar power systems, making the initial investment more affordable. These incentives may include tax credits, rebates, or concessional financing for solar installations.
Benefits to DISCOMs from solar energy integration	
Peak load management	Solar energy integration allows DISCOMs to manage peak loads , especially during daylight hours. This can reduce the strain on the grid and minimizes the need for additional infrastructure to handle peak demand.
Grid stability	Solar energy, when integrated with smart grid technologies, contributes to grid stability. Advanced monitoring and control systems help DISCOMs manage fluctuations in energy production and consumption more efficiently.
Diversification of energy sources:	Integrating solar energy diversifies the energy mix, reducing DISCOMs' dependence on conventional power sources. This diversification contributes to a more resilient and sustainable energy infrastructure.
Regulatory compliance and renewable energy credits	DISCOMs can meet renewable energy purchase obligations (RPOs) more effectively by integrating solar energy into their portfolio. Compliance with RPOs may lead to the accumulation of Renewable Energy Certificates (RECs), which can be traded for financial benefits.
Long-term cost savings	While there may be initial investments in infrastructure, the long-term operational costs associated with solar energy are often lower. DISCOMs can benefit from reduced fuel costs, maintenance expenses, and long-term stability in energy prices.
Demand side management as a tool	Solar integration, when combined with ToD and ToU pricing strategies, encourages consumers to shift their energy consumption to times of abundant solar generation. This aligns consumer behaviour with optimal grid conditions and enhances demand-side management.

Source: MP Ensystems Research, 2024

Overall, consumers gain from lower costs, energy independence, and environmental benefits, while DISCOMs benefit from improved grid management, reduced losses, and compliance with renewable energy targets through solar energy integration. The symbiotic relationship between consumers and DISCOMs in the context of solar RE integration contributes to a more sustainable and efficient energy ecosystem.

Figure 25: General understanding of TOD in the Indian context

Peak load management

- ToD pricing can assist DISCOMs in managing peak loads effectively. By encouraging consumers to shift their energy consumption to off-peak hours when renewable energy generation is high, there can be cases where the grid peak do not coincide with solar generation hours and as prices can be lower in the solar generation hours DISCOMs can optimize grid performance and reduce the need for additional infrastructure to handle peak demand.

Lower carbon intensity grid and environmental benefit

- ToD pricing can raise consumer awareness about the importance of energy conservation and renewable energy utilization. Engaging consumers in energy-efficient practices contributes to a more sustainable and resilient energy ecosystem. Raising awareness about renewable energy sources (RES) and energy efficiency (EE) is beneficial only if it results in a more sustainable grid with lower carbon emissions. However, this outcome is only achievable if the awareness efforts prevent the wasteful curtailment of renewable energy sources.

Cost savings and financial viability

- ToD pricing can contribute to cost savings for DISCOMs by promoting a more balanced distribution of energy demand throughout the day. This can lead to better financial viability for DISCOMs by optimizing the utilization of existing infrastructure.

Grid stability and viability

- Renewable energy sources, especially solar and wind, are intermittent. ToD pricing can incentivize consumers to align their energy usage with periods of higher renewable energy availability, helping DISCOMs better manage grid stability and reliability.

Source: MP Ensystems Research, 2024

In summary, integrating renewable energy with ToD and ToU pricing is crucial for DISCOMs in India to manage peak loads, reduce reliance on conventional sources, ensure grid stability, meet regulatory obligations, achieve cost savings, and contribute to the overall sustainability and resilience of the energy distribution system. Additionally, the lack of ToD systems means that there is a missed opportunity to manage electricity consumption during peak demand periods. This lack of management could lead to increased grid stress and potential blackouts during times of high demand. Furthermore, unmanaged charging scenarios could result in elevated costs related to grid freight, as the lack of intelligent charging mechanisms may lead to suboptimal distribution of electricity.

In the context of this report the ToD tariff is used for minimize the utility generation cost by shifting demand in solar generation period.

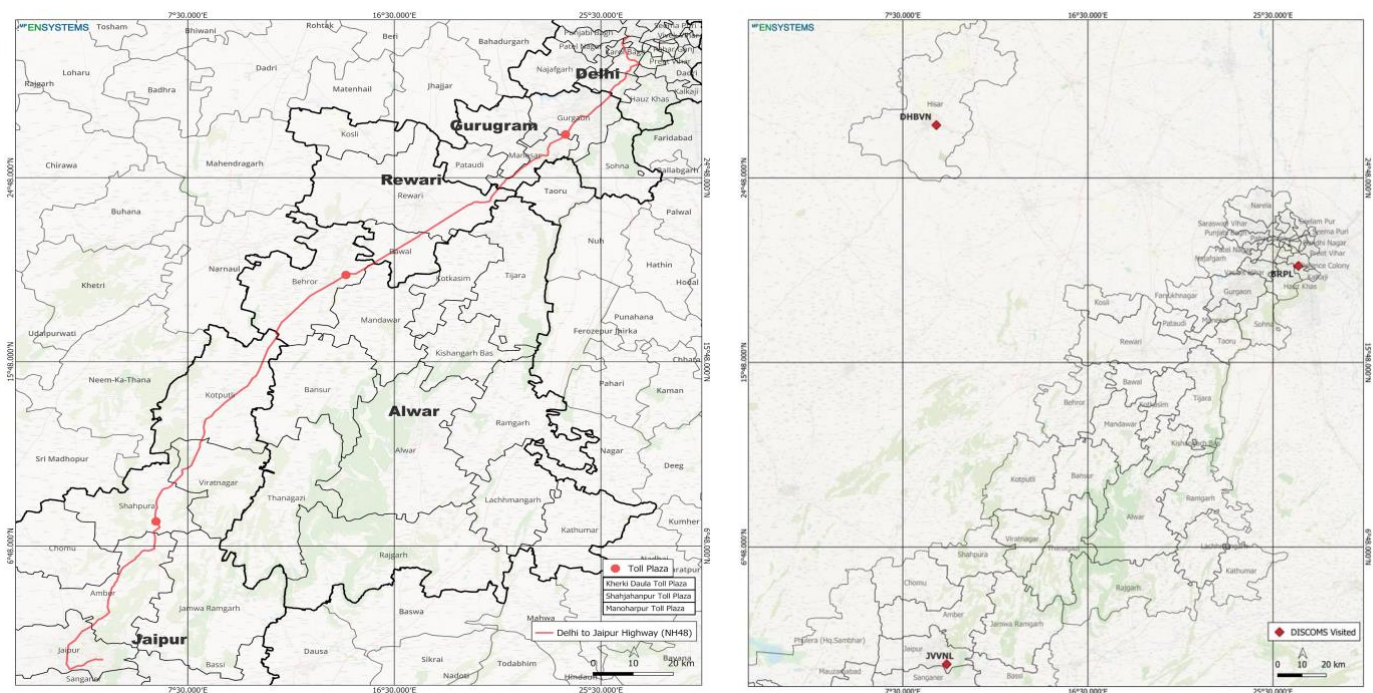
Chapter 3: Understanding impact of tariff structures on charging and grid utilisation - Case study of Delhi-Jaipur corridor

This chapter is structured into two primary sections. The first section delves into the review of state specific tariff orders. The second section details the components of electricity supply cost, tariff calculations along with other related parameters in the Indian context.

Review of state specific tariff orders - Case of Jaipur, Haryana and Delhi: The aim of this subsection is to examine the regulatory framework, tariff structures, and grid infrastructure readiness for implementing smart charging solutions in the Indian states of Jaipur, Haryana and Delhi the selected highway corridor is passing through. Through a review of state-specific tariff orders and stakeholder interactions with DISCOMs, the objective is to understand existing charging tariffs, ToD plans, and stakeholder perspectives on grid stability and EV charging infrastructure. Substation visits provide insights into grid capacity, potential overload scenarios, and opportunities for smart charging optimization. By synthesizing these findings, the aim is to identify challenges and opportunities for integrating electric vehicle charging into the existing grid infrastructure, ultimately guiding the development of strategies for efficient and sustainable EV charging deployment in the region.

Understanding components of electricity supply cost, tariff calculations and defining deferred cost/avoided cost: The aim of this subsection is to elucidate the benefits associated with avoiding grid upgrade costs in Delhi through the implementation of smart charging solutions for EVs. By analysing the specific context of Delhi's electricity supply system, the subsection aims to demonstrate how smart charging strategies can optimize existing infrastructure and defer expensive grid upgrades. It seeks to highlight the economic advantages, including cost savings for utilities, achieved by minimizing the need for capacity additions and transmission network enhancements. Additionally, the subsection aims to underscore the environmental benefits of smart charging, such as reducing carbon emissions and promoting the integration of renewable energy sources. Overall, the aim is to provide a comprehensive understanding of how smart charging initiatives can contribute to a more sustainable, resilient, and cost-effective electricity supply system in Delhi.

Figure 26: Delhi-Jaipur corridor and corresponding discoms visited



3.1 Review of state specific tariff orders - Case of Delhi, Haryana and Jaipur

(Table 4) details a brief review of state specific tariff orders and available ToD plans in EV charging and strategies. This helps us in understanding the suggested tariff structures and their target for structuring the tariffs in this way.

Table 4: State specific tariff orders : Case of Delhi, Haryana and Jaipur

	Sub-Categories	Delhi	Haryana	Rajasthan
Charging tariff (INR/unit ¹⁸)	LT	4.5	6.62	6
	HT	4	6.22	6
Fixed Charges	LT	0	0	40/HP/month
	HT	0	0	135/kVA/month
Domestic Tariff (INR/unit)	-	INR 3.00 (up to first 200 units/month) INR 4.50 (201-400 units/month) INR 6.50 (401-800 units/month)	INR 2.75 (up to first 150 units/month) INR 5.25 (151-250 units/month) INR 6.30 (251-500 units/month)	INR 4.75 (up to first 50 units/month) INR 6.50 (50-150 units/month) INR 7.35 (150-300 units/month)
ToD charges for EVCI (if existing)	Off-peak hours Rebate (Slot 4:00 to 10:00)	20%	INR 4.25/kVAh for 11/33 kV consumers and INR 3.75/kVAh for 66 kV and above consumers	7.5%*
	Peak hours Surcharge (14:00 to 17:00, 22:00 to 01:00)	20%	-	7.50%
ACoS (Average Cost of Supply)		7.43	6.62	7.88
ToD plans in EV charging		Applicable on all consumers (other than Domestic) whose sanctioned load/MDI (whichever is higher) is 10kW/11kVA and above.	Concessional off – peak tariff / night time concession shall be applicable for the EV Charging stations for the entire energy drawl during the off-peak hours.	DISCOMs should study the type of chargers availability, their impact on transformers and system, possibility of integration of smart charger with Smart Meters so as to introduce ToD tariff where such charger/Meters are installed
Existing ToD norms		Applicable on all consumers (other than Domestic) whose sanctioned load/MDI (whichever is higher) is 10kW/11kVA and above.	Applicable only on HT lines	For industrial connections and EVCI

Source: MP Ensystems Research, 2024

¹⁸ 1 unit of electricity in India is equivalent to 1 kWh

3.1.1 Stakeholder interactions and inferences

Reporting findings from stakeholder interaction with:

Jaipur DISCOM | Jaipur Vidyut Vitran Nigam Limited (JVVNL)

- Bulk load connections and substation capacity:** Discussed DISCOM's procedure for allocating bulk load connections. Established that most substations have sufficient capacity for new connections and substation capacity adjustments are made by installing new transformers or removing existing ones if overloaded or underloaded.
- Grid stability and bulk load connections:** DISCOM is not facing any grid network issues due to the connection of bulk loads ranging from 40 MVA to 1 MVA and switching of these bulk loads has not led to congestion or grid stability issues.
- EV charging infrastructure (EVCI) and traffic surveys:** EV chargers connected to the grid are spread across the DISCOM region, and EVCI contribution to the overall load is currently low.
- Time-of-Day (ToD) structure for EV charging demand:** DISCOM does not foresee significant impacts of freight EVCI on the overall load curve with respect to ToD structure. DISCOM requested a presentation on anticipated load from freight EV charging on the Delhi-Jaipur corridor based on traffic and site surveys.
- Load profile data and renewable energy integration:** DISCOM shared utility level load profile data for 22-11-2023 and discussed load shapes and implications for high renewable energy (RE) integration and discussed that they have managed to shift peak load¹⁹ to the afternoon period when solar generation is available.
- Management of agricultural load during solar period:** Despite high agricultural load during the solar period, DISCOM can manage this load within a very short period.
- Consideration of relevant corridor for study:** It was suggested that the Delhi-Jaipur corridor (NH48) might be of less relevance, when the new NE4 highway is available, and most traffic is likely to flow on it.

Haryana DISCOM | Dakshin Haryana Bijli Vitran Nigam (DHBVN)

- Charging times, space constraints, and economics of charging:** Explored the challenges posed by lengthy charging times and space limitations in urban areas such as queuing of charging, space constraints and land cost for charging hubs etc. and discussed the economic implications of charging infrastructure installation and maintenance, considering both public and private investment models.
- Popularizing EVs and charging and roadmap towards freight:** Discussed strategies to increase EV adoption among consumers, including incentives, awareness campaigns, and infrastructure expansion and discussed the strong need for a roadmap for integrating electric freight vehicles into existing transport systems, considering logistics, charging infrastructure, and regulatory frameworks.
- Railway system's charging infrastructure development:** Discussed the charging solutions adopted by railway systems for electric vehicles and the maximum demand during peak times and the differences between demand and normal periods.
- Study of existing charging stations and growth expectations:** Discussed the need for analysis of the current status of charging stations in comparison to the expected growth of EVs. Explored discrepancies between projected growth and the actual expansion of charging infrastructure.

¹⁹ Shifting peak load happens through a connection of substation for a single line there is no extra cost involved in any addition of lines for this load.

5. **Per month demand for charging and impact on power purchase costs:** Explored the monthly demand for charging and its effects on electricity purchase costs and discussed the potential impact of increased EV charging on the power grid and energy suppliers.
6. **Smart charging project analysis parameters:** Explored the current parameters utilized for analysing smart charging and identified areas for further development, improvement in analysis methodologies and also discussed the need for conducting a thorough analysis on one site as a pilot and preparing a report with parameters assumed, scalable along the corridor on different sites.

Delhi discom | BSES Rajdhani power Ltd. (BRPLI)

1. **Peak demand evaluation and land allocation:** Discussion on evaluation of peak demand in various states, including seasonal peaks due to diverse agricultural and freight-based loads. Land allocation by relevant government authorities for charging infrastructure with favourable tariff structures.
2. **EV charging scenario in Delhi:** Discussion on public charging segments (30% of total charging) Road Charging: Intermittent charging pattern necessitates the introduction of ToD charges for road charging. Hub Charging (20-30% vehicles parked overnight): Majority prefer overnight charging, willing to pay extra during peak hours. Bus Charging (5% fleet for emergency use): 80% fleet always operational, 15% not in use due to factors like driver shift changes. Private Charging Segments (60-70%): Chargers installed at home with connected load details for different EV chargers.
3. **Tariff structure and cost recovery²⁰:** ToD tariff structures as an effective option for DISCOMs to recover higher power purchase costs from short-term sources. Challenges in implementation due to a lack of time-enabled chargers.
4. **Infrastructure challenges and network considerations:** Recovering the cost of power purchase, especially for categories exceeding 10KW. Imperative for Charge Point Operators (CPOs) to install time-enabled chargers with pop-up notifications during peak hours.
5. **Freight EV charging:** Is it possible to develop a pilot for EV charging intervention in certain freight segments? BRPL suggested developing collaboration with logistics or transportation companies to implement a pilot project on a small scale for smart charging. Discussion about Implementation of a pilot project at a small scale which can then be scaled up at a larger scale with the approval of the regulatory commission.

Substation visit: Jaipur (220 kV substation, Hisar) | November, 2023

The transmission substation primarily caters to industrial consumers. However, it is currently observing nearly overloading conditions in the period starting from **8:00 AM to 6:00 PM**. In anticipation of potential overload, a contingency plan involves **shifting consumers to alternate substations**. The **total capacity of the substation stands at 400 MVA**, distributed across **different transformers (160 + 100 + 2*50 + 40)**. To address potential overload, the option to upgrade the substation's capacity through additional transformer installation²¹ is often considered. This decision stems from an analysis of demand projections, prompting plans for either substation upgrades or the establishment of new substations in different locations. Connections to these substations are sanctioned through DISCOMs. Notably, while the overall substation capacity might not be fully utilized, localized congestion on specific lines during peak periods, especially in summer, can lead to overloading. To address this, load profiles for maximum loading days during summers have been collected, aiding in strategic planning and resource allocation at various sites.

²⁰ This was a discussion held with DISCOM official and they expressed this concern and their opinion during discussions in context of managed charging.

²¹ Grid upgradation cost = 12.5 million INR/MW

The substation is equipped to cater to any forthcoming demand in the near future. Substations in the area mainly cater industrial consumers. There are no issues of load shedding in the area and power supply during the peak season is catered to properly. Any near future demand for power by EV charging stations can be managed easily. Seasonal peak demand is observed during the summer season. During the day, peak load is usually observed around evenings, but consumption is relatively low at night, which is an option to be considered for smart charging of trucks. Headroom is available for new connections in most of the substations. Augmentation of grid infrastructure has been done in recent years to manage increasing power demand.

Summary of the visit

Following stakeholder meetings, our analysis reveals several key insights regarding the current state of substations and the integration of EV charging stations within the network. From the stakeholder discussion it was revealed that most substations presently possess ample capacity for new connections. The process of adjusting substation capacity, typically through installing or removing transformers, has been effective in addressing any overloading or underloading issues. Importantly, the connection of bulk loads, ranging from **40 MVA to 1 MVA**, has not caused grid congestion or stability concerns from the perspective of DISCOMs.

In our visit to a substation, which primarily caters to industrial loads, we identified a significant peak in usage from **9:00 AM to 6:00 PM**, aligning closely with the operational hours of manufacturing industries. HDVs operate on an ad-hoc basis, with asset being used as and when there is demand for freight. The only constraint to their usage in and around Delhi is during the ban time.

Our stakeholder engagements also involved ground surveys along designated corridors to comprehend driving behaviours and parking patterns. **The collected data indicated a lack of consistent patterns in driver behaviour, with vehicle resting and stoppage seemingly determined on a case-by-case basis by individual drivers.** As a result, while we gleaned valuable insights, the available information may not be comprehensive enough to sufficiently optimize grid utilization in freight EV charging. Regarding the proposed installation of EV charging stations near highways, we found that most EV freight fleets are expected to have dedicated captive charging stations at logistic parks or base stations. Public charging stations along these corridors are aimed to primarily facilitate opportunity charging during vehicle rest stops.

However, the challenge arises with the constraints of opportunity charging, where the relatively short plug-in times for EVs impose strict limitations on managing charging loads in this specific context. To study this further it is also important to understand the components of electricity supply cost, the calculation of tariffs in order to get an overview of tariff, charging demand and other relevant parameters.

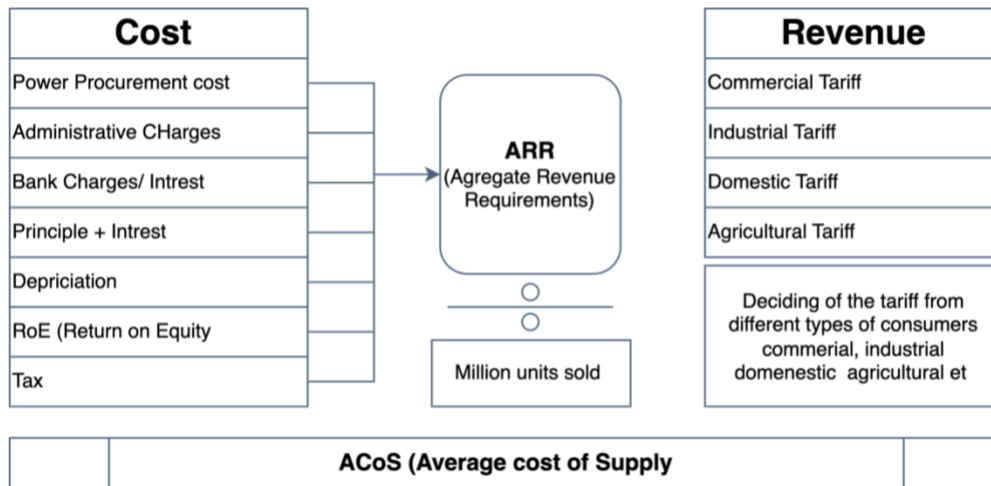
3.2 Understanding components of electricity supply cost, tariff calculations and defining deferred cost/avoided cost

The calculation of avoided or deferred grid costs involves a multifaceted analysis that takes into account various factors such as EV freight, generation costs under ToD systems, network upgrade savings, and the added cost of implementing smart chargers and associated applications. By intelligently managing EV charging patterns and incorporating smart charging solutions, utilities can reduce the strain on the grid, minimize overall generation costs, and avoid or defer expensive network upgrades. The advancement of technology has led to the development of smart chargers, which have revolutionized the way electricity grids operate. These chargers are designed to communicate with the grid and adjust power consumption according to the available supply. This feature enables them to optimize energy usage by charging electric vehicles during off-peak hours when electricity demand is low. This reduces the strain on the grid during peak hours and helps to balance the load.

Despite the benefits of smart chargers, it's important to acknowledge that the implementation of these chargers leads to added costs. The upfront investment in deploying these technologies needs to be considered against the potential

long-term benefits in terms of avoided grid costs, generation cost savings, and network upgrade savings. This means that a careful cost-benefit analysis must be conducted to determine the net economic and operational impact of integrating smart charging solutions into the evolving landscape of the electricity grid which also includes a careful analysis of a cost of supply of power and its components and factors influencing it.

Figure 27: Components of ACoS (Average cost of supply)



Source: MP Ensystems Research, 2024

- **Power procurement costs:** The cost to generate power is driven by the overall mix of generation, the cost of fuel for each generation source, the efficiency of these generators, and the capital and operational costs of each generator. The cost of integration of renewable energy has been considered as part of the power purchase costs²² in this analysis. In addition, this component also accounts for (technical) losses incurred in transmission and distribution.
- **Distribution charges:** This is the cost to distribute and transform, from higher to lower voltages, the power from transmission lines to individual customers. It is driven by the cost to build and maintain the infrastructure to deliver power and to comply with the Renewable Power Purchase Obligations for each state.
- **Transmission charges:** This is the cost to transport high-voltage power from the generators over inter-state and intra-state lines to the DISCOM infrastructure. It is driven by the cost of building and maintaining these lines as India's need for electricity grows.
- **Cross-subsidy charges:** This is the cost for commercial and industrial customers to offset the total delivered cost of electricity to domestic customers. It is often driven by political considerations and dynamics in each state.

²² These costs are taken from CEEW's long-term (mid-century) projections for India based on the results of energy modelling (CEEW, 2017).

Components of cost of supply and the factors that influence them are as follows²³:

Table 5: Components of cost of supply (Delhi)

Utility (FY2019-2020) ²⁴	PPC (Power Purchase Cost (Rs))	Transmission cost (Rs)	Distribution cost (Rs)	Cross subsidy charges (Rs)
TPDPL (Tata Power Delhi Distribution Limited)	6.35	1.02	1.84	2.21
BRPL BSES Rajdhani Power Limited	6.51	1.05	1.89	2.1
BYPL BSES Yamuna Power Limited	6.51	1.13	1.5	2.29

Source: MP Ensystems Research, 2024

The above table gives the different components of cost of supply in Delhi, to understand their contribution to total cost. India is experiencing 5% to 6% CAGR in electricity demand²⁵, which requires optimal planning for upgradation and operation of generation resources, transmission and distribution network assets. Smart charging can help in optimal use of the current resources and deferring the investment in new generation, transmission and distribution capacities. The scope of smart charging for avoiding grid costs is discussed below:

- **Avoided power purchase cost:** Power purchase cost depends on total energy demand, peak demand, variable and fixed cost of generators and power market cost. Appropriate ToD/ToU pricing structures can shift the EV charging demand to reduce peak demand and can also help integration of more RE generators which have lower energy charges than conventional power plants. This can help the utility to reduce the power purchase cost and utilise the available generation resources optimally.
- **Avoided distribution upgradation cost:** Smart charging of EVs can also help operate the local distribution network optimally by minimizing the feeder level/ substation level overloading. The stakeholder discussion (BRPL, Delhi DISCOM) revealed an estimate of **1 Cr to 1.25 Cr (10-15 million USD) per MW** as a general grid upgradation cost. In India, the connection for new load is given ensuring availability of enough capacity at substation/feeder serving that area. Smart charging can help increase the substation headroom availability and can help in avoiding capacity addition requirement.
- **Avoided transmission upgradation cost:** Smart charging has very little scope in avoiding transmission cost as the transmission planning is done on a larger scale and considers generation capacity addition. For integrating 500 GW of RE generators by 2030 the transmission network in India is being currently upgraded²⁶.

The estimation of avoided costs associated with additional power (MW) and energy (MWh) demand from freight electric vehicle (EV) charging depends on the implementation of smart charging strategies. **This involves managing the extra demand without the need for constructing new power generation plants or upgrading existing distribution and transmission networks.** To determine the achievable potential, it is essential to account for constraints related to the timing of freight EV charging. Lastly, the market potential can be calculated by considering the availability and

²³ <https://www.ceew.in/sites/default/files/CEEW-Retail-Tariffs-for-Electricity-Consumers-in-Mumbai-10Jun18.pdf>

²⁴ These are all electricity distribution companies operating in Delhi, India.

²⁵ <https://www.brookings.edu/wp-content/uploads/2018/10/The-future-of-Indian-electricity-demand.pdf>

²⁶CEA, https://cea.nic.in/wpcontent/uploads/notification/2022/12/CEA_Tx_Plan_for_500GW_Non_fossil_capacity_by_2030.pdf

adoption of smart charging technologies currently present in the market, which can be implemented on a larger scale. In Chapter 4, we have explored the implications of shifting electric vehicle (EV) freight charging demand to coincide with solar hours using ToD pricing structure to decrease the power purchase cost to utility.

Chapter 4: ToD economic modelling exercise

This chapter is structured into 7 major sections with each section attempts to explain a specific aspect of the ToD/ToU model created. The first 2 section aims to explain the concept and inception of the model and the broad parameters that come into play and subsequent sections attempts to explain the working, outputs and limitations of the model.

Creating a model for analysis of freight charging: The aim of this subsection is to delineate the key procedural steps involved in developing a comprehensive model for analysing **charging scenarios related to solar periods and EV freight charging**. It outlines the process of scenario design, focusing on defining various charging scenarios under different tariff structures. Additionally, it explains the analysis of the charging framework, detailing the incorporation of **historical data and projected trends to inform assumptions and parameters**. The subsection also highlights the implementation of an **economic ToD model**, aimed at estimating both consumer costs for EV charging and utility costs for meeting EV electricity demand. Ultimately, it aims to facilitate an understanding of how variations in renewable energy integration and tariff structures impact the economic feasibility, aligning EV charging with solar generation periods.

Broad model parameters: The aim of this subsection is to emphasize the importance of integrating key parameters such as parking profiles, charging profiles, tariff structures, and traffic count data into the model for enhancing its accuracy and effectiveness. By including these parameters, the subsection aims to facilitate scenario diversification, allowing for the simulation of multiple real-world conditions and their implications on EV charging infrastructure and utility costs. Additionally, the subsection seeks to highlight the significance of utilizing the model outputs to inform policy and strategy formulation, particularly in optimizing EV charging practices, promoting renewable energy utilization, and enhancing overall grid management efficiency. Ultimately, the aim is to provide valuable insights for stakeholders to make informed decisions regarding EV infrastructure development, tariff structuring, and sustainable energy integration.

Working of the model and calculation matrix: The aim of this subsection is to outline the methodology and key assumptions used in the model for analysing EV charging demand. It provides a structured approach, including stages such as creating parking profiles, correlating data with traffic counts, and defining scenarios for analysis. The subsection also elucidates major assumptions regarding charging tariffs, renewable energy costs, and EV stock increases over time. By presenting these inputs and assumptions, the subsection sets the foundation for understanding how the model predicts charging behaviour, costs, and potential benefits for consumers and utility providers

Model outputs: The aim of this subsection is to analyse the impact of integrating renewable energy sources, particularly solar energy, into the EV charging infrastructure. Specifically, it aims to understand how different scenarios of renewable energy integration and solar tariff decreases through rebates affect utility profits and greenhouse gas emissions. By examining various levels of renewable energy integration and shifting EV charging demand to solar hours, the subsection seeks to provide insights into the potential benefits for utilities, consumers, and the environment. Additionally, it aims to highlight the practical implications of these scenarios on utility operations and consumer behaviour, ultimately informing decision-making processes regarding sustainable energy practices and EV adoption strategies.

Output inferences: This section combines the outputs and provides inferences from the extrapolated graphs and analysis done in outputs in a simple matrix format

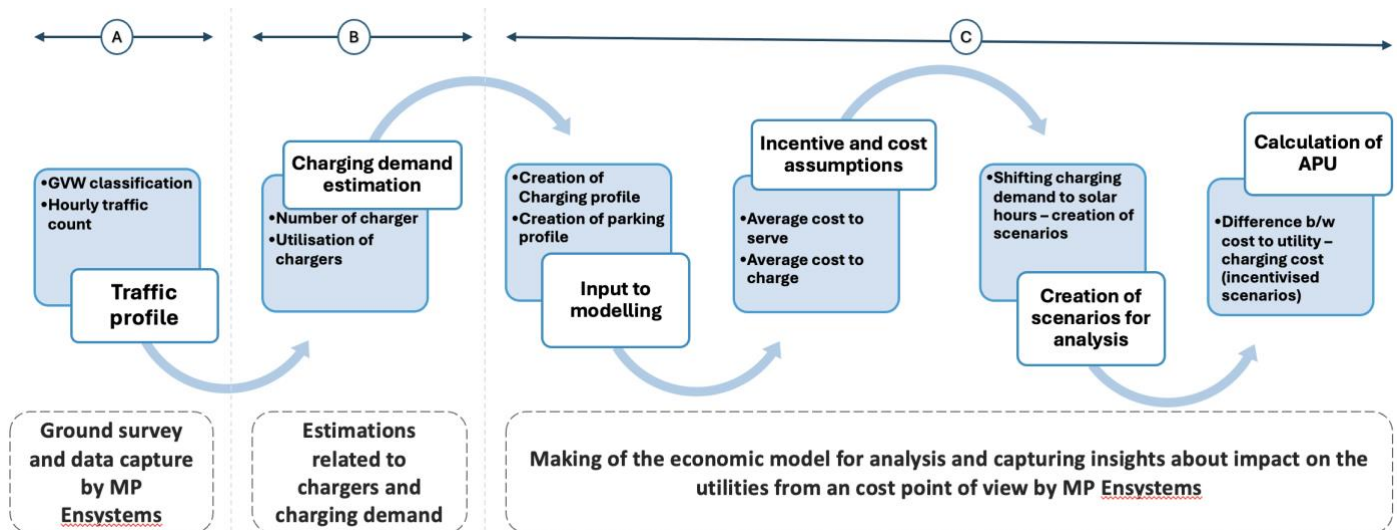
Limitations: This section aims to identify the model as well as overall limitations of RE integration in freight EV charging and smart charging in the Indian context

4.1 Creating a model for analysis of freight charging

To address the challenges mentioned above, a generalised excel-based model has been developed that serves as a preliminary framework for evaluating the cost implications of shifting EV freight charging to RE (solar) periods. In the context of renewable energy (RE) solar, the focus is on evaluating the costs for utilities and consumers associated with EV charging, as well as estimating the potential profits utilities can achieve. This analysis includes the impact of encouraging consumers to charge during solar production hours by offering reduced tariffs, thereby incentivizing solar period charging. With the assumption that solar integration into the energy mix will increase in the coming years, attempting to shift the additional load to the solar hours can be explored here.

The primary focus of the model is to understand the cost implication of shifting EV charging demand into solar hours. By shifting charging to solar periods, it is possible to reduce the load on the grid during peak demand hours, thereby reducing the strain on the existing infrastructure and minimizing the cost of electricity for consumers. This is assuming that the peak demand other than EVs is not in the solar period. Overall, the model offers **scenario wise cost implications** related to freight charging. The subsequent sections explain the working of the model.

Figure 28: Process flow of the overall exercise



Source: MP Ensystems Research, 2024

Model introduction and objective

The increasing integration of renewable energy (RE), particularly solar power, in the power sector is anticipated to reduce the cost of electricity generation during solar hours. To leverage this, we are exploring the potential of EV freight charging load adjustment within these solar periods through the implementation of ToD tariff structures. Our model assesses **three scenarios** focusing on EV charging convergence during solar hours, each associated with **specific ToD structures**. These **scenarios aim to estimate the cost implications linked to shifting EV freight charging to coincide with solar generation periods**. Our analysis spans from 2023 to 2030, projecting the corresponding values. In determining **the average cost to serve (ACoS), which encapsulates utility costs associated with serving energy to consumers, including variable energy charges, we've referenced the IEX market slot-wise rates for power generation costs**.

The evaluation involves calculating two primary parameters: first, the cost borne by consumers for charging their EV freight vehicles which is Average Cost to Charge (ACC), and second, the cost that utilities incur to meet the electricity demand from these EV freight vehicles during both solar and non-solar hours ACoS. By computing the disparity between ACoS and ACC, we derive an indicator of cost benefit to the utility (APU-Average profit to utility), highlighting potential efficiencies gained through this shift towards aligning EV charging with solar generation periods.

The model aims to provide insights into the **economic implications of encouraging EV freight charging during certain time periods** (solar periods in this case). By assessing both **consumer** and **utility costs**, it aims to quantify the potential costs and benefits derived from this shift, contributing to a more efficient utilization of renewable energy sources and optimizing utility operations.

The model's core objectives are:

1. Providing nuanced insights into the economic implications of promoting EV freight charging during solar periods.
2. By quantifying costs incurred by both consumers and utility providers, it aims to delineate potential cost benefits, in turn, facilitating more efficient utilization of solar energy resources, optimizes utility operations, and informs strategic decisions in policy formulation, utility planning, and infrastructure development in the dynamic landscape of EV integration and renewable energy utilization.

The section below highlights the model's framework, its key components, and its significance in providing insights into the **economic implications of EV freight charging alignment with solar/RE periods**.

4.1.3 Key components of analysis through the model

The model's framework is structured around 2 key components:

1. **Scenario analysis:** Encompassing three distinct scenarios (sub-point A), the model evaluates the impact of increasing RE penetration on power generation costs during solar hours. Additionally, it incorporates ToD tariff structures to incentivize the alignment of EV freight charging with solar generation periods.
 - A. **Scenario design:** Defining three scenarios and cases to assess the impact of shifting EV freight charging to solar periods under different ToD tariff structures.
 - B. **Analysis of charging framework:** Developing an analytical framework incorporating the defined scenarios and utilizing charging demand data shared by ICCT³.
 - C. **Economic ToD model:** Designing an excel model to estimate consumer costs for EV charging and utility costs for meeting EV electricity demand during solar and non-solar hours.
 - D. **Impact evaluation:** Conducting analysis to understand and infer how variations in RE penetration and tariff structures affect cost implications.
2. **Data integration and parameterization:** Utilizing a comprehensive dataset spanning the period from 2023 to 2030, the model references IEX (India Energy exchange) market slot-wise rates as a benchmark for ACoS. Parameters include estimating consumer costs for EV charging, utility costs for supplying EV electricity demand during both solar and non-solar hours.

4.2 Broad model parameters

This section outlines the framework, data considerations, parameters, and key steps involved in creating a comprehensive model for analysing charging scenarios concerning solar periods and EV freight charging. Adjustments or enhancements to this model could involve finer granularity in data analysis, validation through real-world data, and exploring additional factors and RE sources influencing charging behaviours and utility costs.

Given below are the broad parameters, their general understanding and use in the context of the modelling exercise.

4.2.1 Parking profile

Relevance to the model development

1. **Impact on charging behaviour:** Incorporating parking profiles involves understanding the duration and frequency of vehicle parking. This data helps simulate realistic charging behaviours, considering varying durations of EVs being parked and available charging opportunities during these times.
2. **Charging availability and utilization:** Parking profiles influence the availability of charging stations during specific time frames. Models considering these profiles can better simulate charging demand, optimizing the use of available charging infrastructure.

4.2.2 Charging profile/Charging demand estimation

Relevance to model development:

Cost-benefit analysis: Analysing the impact of solar charging shift within the model assesses the cost implications for consumers and utilities. It highlights potential cost savings due to reduced grid reliance during solar hours.

Understanding in context of modelling exercise: Utilizing the ICCT model data³ of charging demand for fast, ultrafast and overnight charging demand profile for 24 hours is created. 2 cases are made for depot charging considering 2 distinct slots of charging keeping the utilisation same. The charging demand from fast and ultrafast charging remain same for both the cases added to both cases giving total charging demand for case 1 and case 2 and then 3 distinct scenarios are made for understanding shifting of charging demand to solar hours followed by performing calculation using ToD/ToU obtaining ACoS, ACC and APU.

4.2.3 Tariff structures

Relevance to model development:

1. **Diverse tariff structures:** Such scenarios enable the assessment of consumer charging cost to different utility pricing strategies and their impact on EV charging.
2. **Incentivizing optimal charging:** Tariff scenarios aligned with smart charging strategies can encourage users to charge their EVs during off-peak or solar hours. Models incorporating these scenarios can project potential cost savings for consumers and utilities, based on their tariff adoption.

Understanding in context of modelling exercise: In this part of the analysis, we change different tariff structures while shifting the load in the solar hours to understand the impact of tariff to average cost to utility and cost to charging.

4.2.4 Traffic count

Relevance to model development:

1. **Estimation of slots:** Traffic count data aids in undertaking the live count of vehicles in a 24 hour cycle. Integrating this parameter helps in traffic movement and stoppage time slots along the corridor
- The traffic count data is not directly used as an input in the model for any kind of analysis, it is only used to understand the traffic flow through the Delhi-Jaipur corridor.

4.3 Working of the model and calculation matrix

4.3.1 Model initiation and understanding through a typical case

We integrate data provided by the **ICCT model**³, which includes the number of chargers and their charging capacity. Using this data, we generate charging demand for fast, ultrafast, and depot charging and also consider the charging sessions for fast, Ultrafast and depot charging. The model encompasses 2 cases and three distinct scenarios, including the (S0) Business-As-Usual (BAU) scenario along with Scenario 1, Scenario 2, and Scenario 3, depicting a least aggressive approach, aggressive approach and the most aggressive approach, respectively.

The detailed cases and scenarios mean:

Cases are modelled for fast + ultrafast charging, and depot charging.

For opportunity chargers utilization, parking profile data is used along with ICCT utilization assumption data³. For overnight charging (depot charging), two cases are created:

- **Case1:** Depot charging is presumed to occur exclusively during night-time hours, specifically from 22:00 PM to 6:00 AM, spanning a continuous period of 8 hours. Charging demand from fast and ultrafast charging is also added to get total charging demand.
- **Case2:** Depot charging occurs during periods of low traffic flow along the corridor, as determined by data from traffic surveys. Based on this data, two time slots have been pinpointed for depot charging: 7:00 AM to 11:00 AM and 4:00 PM to 8:00 PM. Charging demand from fast and ultrafast charging is also added to get total charging demand.

Within each case, 3 scenarios are modelled for shifting of EV charging demand in solar hours. For each scenario, a threshold demand is calculated. And the charging demand in non-solar hours above threshold demand is shifted in solar hours

- **BAU Scenario:** This is base case scenario where charging demand is estimated based on survey data, ICCT model output³ etc. without considering any shift in solar hours.
- **Scenario 1 or S1:** The approach involves using the hourly average charging demand as the threshold. Any additional demand during non-solar hours beyond this threshold is shifted to solar hours. **A rebate of 0.5 INR/kWh is offered for shifting this demand.**
- **Scenario 2 or S2:** In Scenario 2 (S2), the threshold is set at 50% of the hourly average demand. Any additional demand during non-solar hours exceeding this threshold is moved to solar hours. **A rebate of 1 INR/kWh is provided for shifting this demand.**
- **Scenario 3 or S3:** Scenario 3 (S3) adopts a zero threshold, meaning all demand during non-solar hours is shifted to solar hours. **A rebate of 1.5 INR/kWh is offered for this demand shifting in this scenario.**

The typical case given below tries to explain the scenarios, decisions and steps of the model in detail.

4.3.2 Stages of model run and calculations

Example: In a particular case, the steps followed to make the model and retrieve an output are as mentioned below:

Step 1:

- Initial steps involve using data on charging demand for chargers, Depot charging and fast+ ultra-fast charging
- From the data provided, we understand that there are 2 kinds of charging considered - depot charging and fast and ultrafast charging (also known as opportunity charging)

Calculations:

- **For fast chargers:**

- Utilisation session time interval 1.5 hours
- Number of slots in a day = 16
- Utilisation session (number of vehicles in each session) profile is interpolated for 24 hours slots
- 24 hours profile is normalised and used for % utilisation profile for fast charger
- **For ultrafast charger:**
 - Utilisation session time interval 0.5 hours
 - Number of slots in a day = 48
 - Utilisation session (Number of vehicles in each session) profile is interpolated for 24 hours slots
 - 24 hours profile is normalised and used for % utilisation for fast charger
- **For depot charging**
 - Case 1: Charging happening in one continuous 8 hr slot
 - Case 2: Charging happening in two - 4-hrs slots) keeping the utilisation percentage same as case 1
- **Total charging demand for year 2023, 2025, 2027, 2030**

- **Case 1:** (Fast and ultrafast charging demand) + depot charging demand (8 hr continuous slot) = **total charging demand case 1**
- **Case 2:** Fast and ultrafast charging demand) + depot charging demand (two 4 hour slots) = **total charging demand case 2**

Step 2: The analysis focuses on the total charging demands, adjusted to correspond with solar hours slots and calculation of Average cost to serve and average cost to charge

- S0 (BAU): Represents the business-as-usual scenario under current conditions.
- S1: Shifts charging demand to solar hours, **(additional charging demand hence the charging demand above average in non-solar hours is shifted to solar hours)**
- S2: Similar to S1 but with 50% of additional charging in the non-solar hours and charging needs shifted to solar hours.
- S3: Another variation with 100% of parking hence charging demand in the non-solar hours and charging needs aligning with solar hours.

Calculations:

The Calculation of Average Cost to Serve (ACoS) and Average Cost to Charge (ACC) for each scenario (BAU, Scenario 1, Scenario 2, Scenario 3). This calculation yields the total cost incurred by the utility and the cost borne by individuals for charging during those hours.

Step 3:

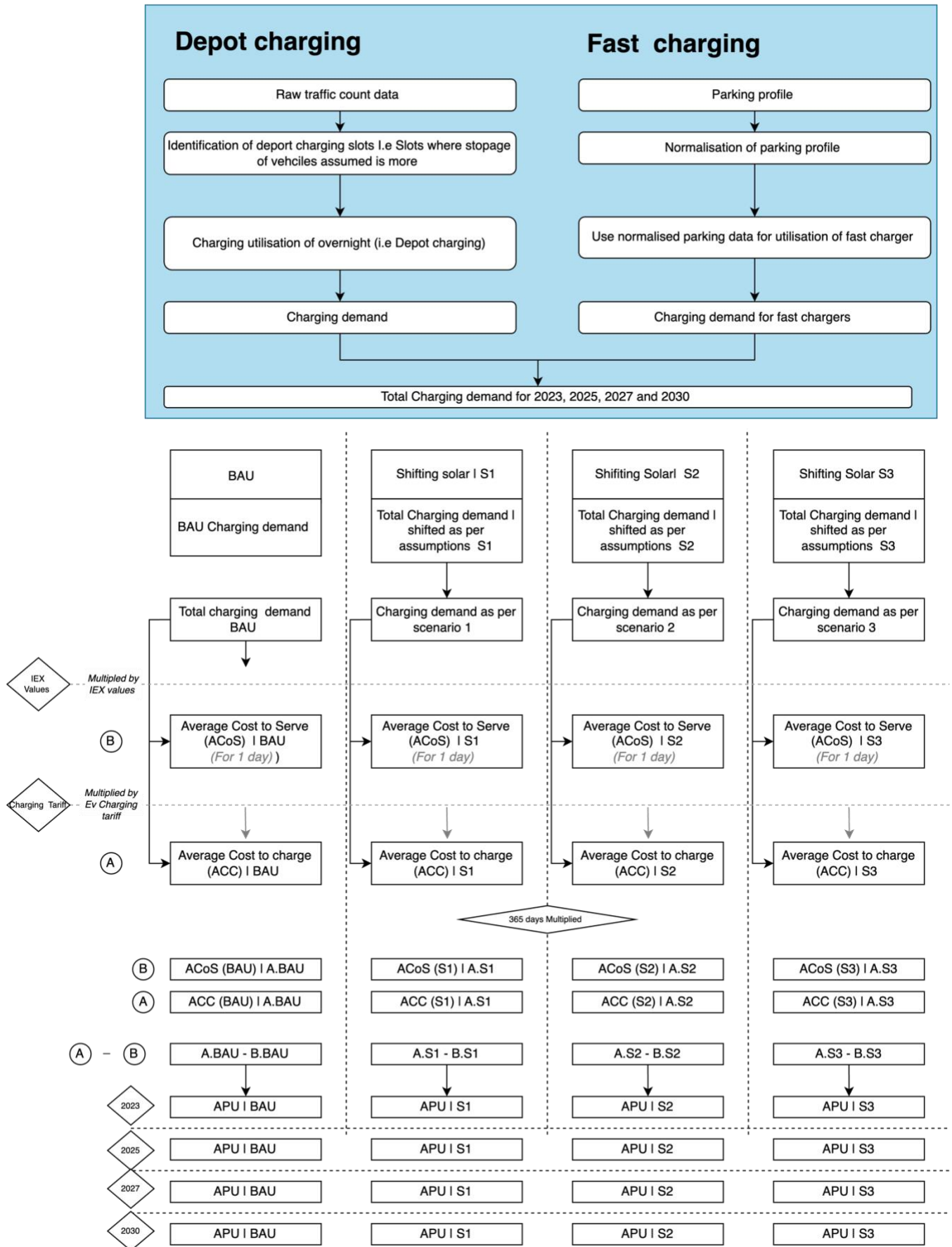
- By subtracting the average cost to serve from the average cost to charge extrapolated in stage 2, the average profit or loss to the utility for the 24-hour (1 day) period can be determined.

Calculations:

Average cost to charge (ACC) - Average cost to serve (ACoS) = Average profit to utility (for BAU, scenario 1, scenario 2 and scenario 3)

Figure 29 shows a generalised working calculation of the model. To understand the steps taken in detailed a typical case is explained to understand the flow of the model steps and obtaining of the output.

Figure 29: Model working - Flowchart



Source: MP Ensystems Research, 2024

4.4 Inputs and assumption

4.4.1 Model assumptions:

The BAU EV charging demand is estimated using data received from ICCT model output³. For opportunity chargers utilization, parking profile data is used along with ICCT utilization assumption data³. For depot charging, two cases are created:

- Case 1: Assuming depot charging takes place continuously (8 hrs continuous slot)
- Case 2: Depot charging takes place when the traffic count across the corridor is low (7:00 AM to 10:00 AM & 16:00 PM to 19:00 PM).

Table below shows the data and assumptions used for estimation of slot wise charging demand.

Table 6: EV charging output data from ICCT³ and interpretations of MP Ensystems

Parameter	Explanation
Data	• Number of chargers and total capacity - ICCT model output³ • Session wise utilization for fast and ultra-fast chargers - ICCT utilization assumptions³ • Overnight charger sessions utilization assumptions -ICCT utilization assumptions³ • Traffic count data is used to identify depot charging slots - Survey data collection • Using IEX values as proxy for ACoS calculations
Assumptions	• For case 1 : Overnight charging slot is assumed to be 22 pm to 5 am • For case 2: Overnight charging (Depot charging) slots are assumed to be slots with low traffic count i.e. 7 am to 10 am & 16 pm to 19 pm • Solar hours are considered to be 6 from 10:00 am to 16:00 pm

Source: MP Ensystems Research, 2024

It is important to note that **this analysis focuses solely on understanding the impact of the relationship between charging demand, tariff, and costs for utilities and consumers.** Other factors required for a real-world trial are not considered here. This analysis assumes that there is no existing load during the specified solar hours for utilities and that freight driving and charging behaviour can be modified based on tariffs.

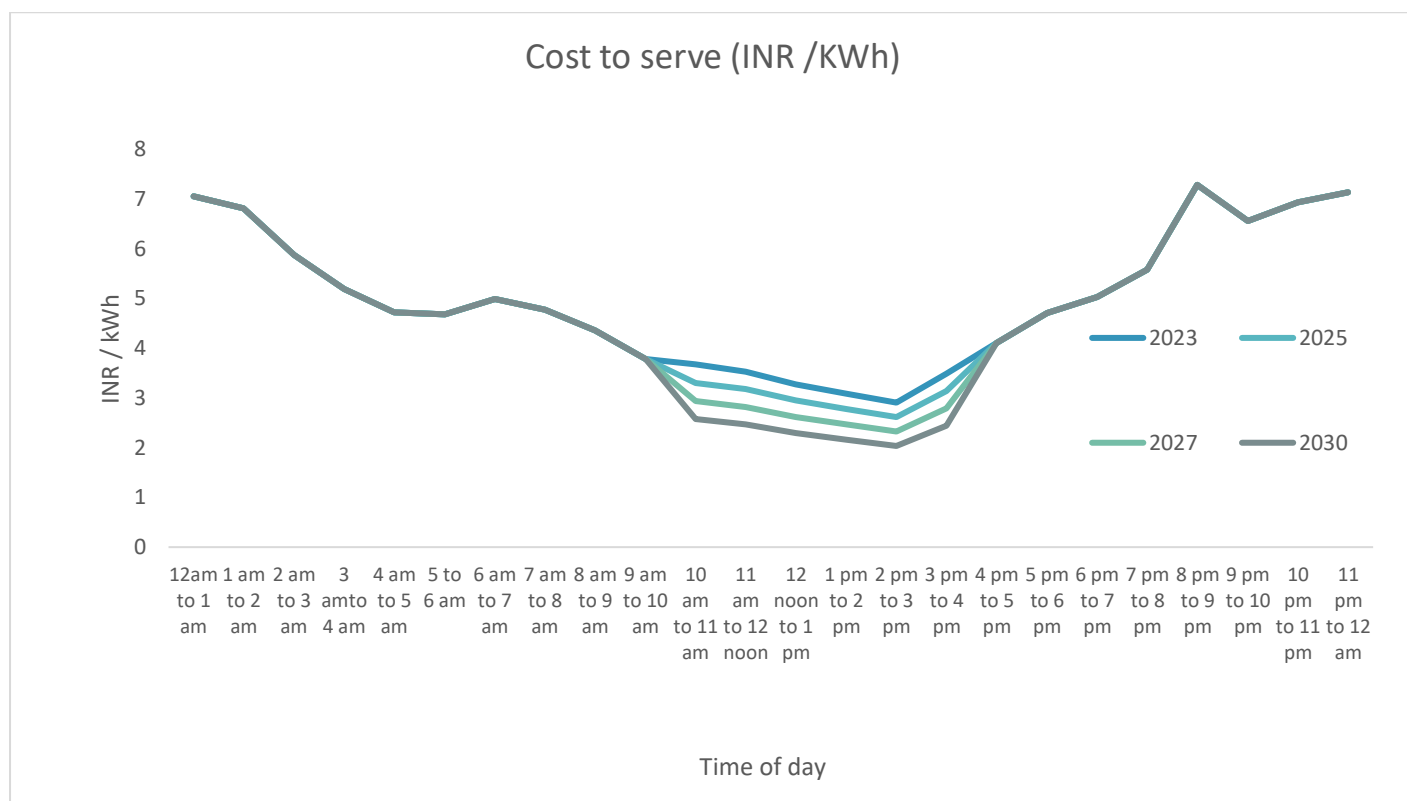
4.4.2 Cost to serve and EV Tariff

Types of costs

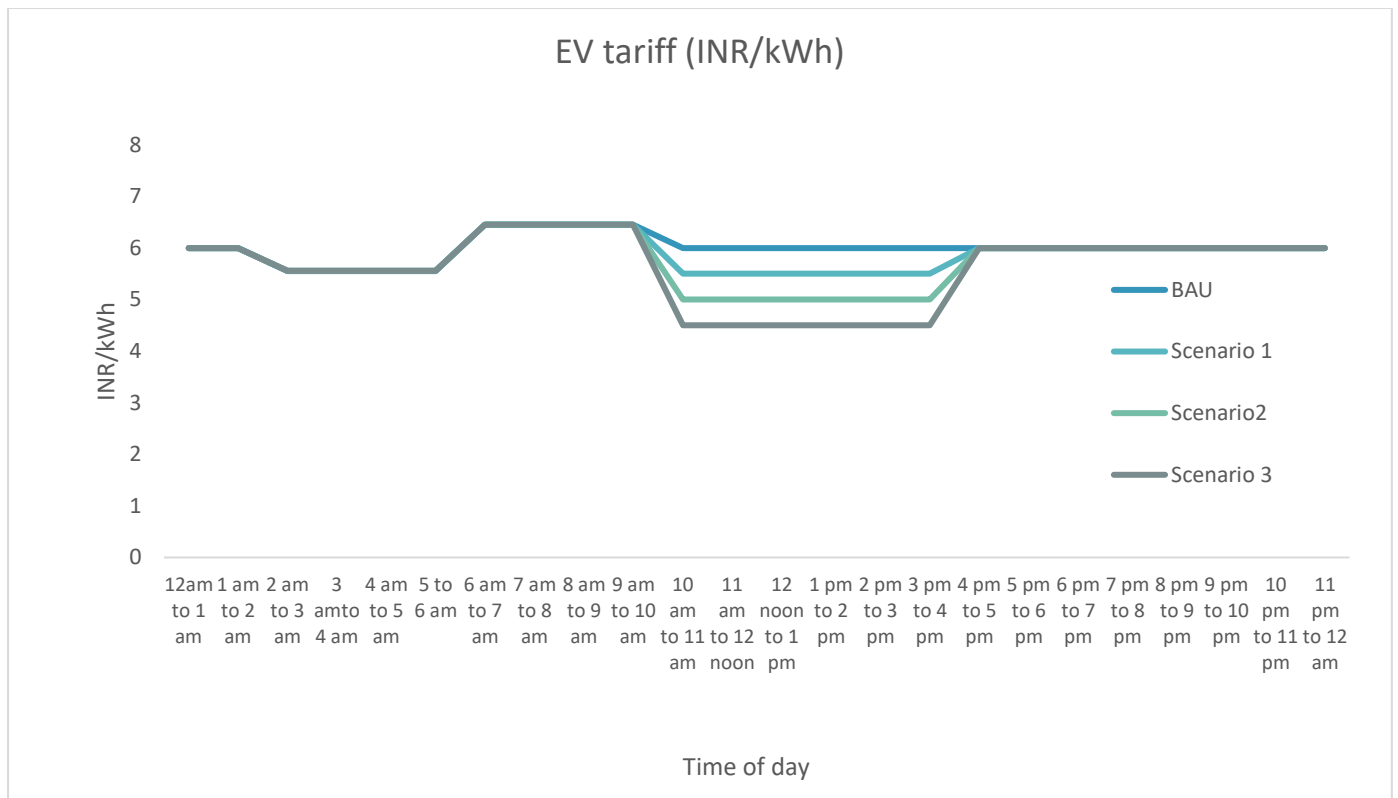
1. **Consumer cost for EV charging:** Estimating the cost borne by consumers for charging their EV freight vehicles, considering the specified ToD tariff structures during solar and non-solar hours.
2. **Utility cost for electricity demand from EVs:** Evaluating the cost incurred by the utility to fulfil the electricity demand from EV freight vehicles during solar and non-solar hours.²⁷
3. **Cost-benefit indicator (APU - average profit to utility):** Calculating the difference between ACoS (Average Cost to Serve) and ACC (Average Cost to Charge) as an indicator of cost-benefit to the utility provider.

The graphs below consider the assumptions regarding the cost to serve and EV tariff across scenarios and years. For 2023, the cost to serve is assumed to be equal to the IEX market price for a typical day in 2023. For the years 2025, 2027, and 2030, the cost to serve is assumed to be reduced by a certain percentage due to higher solar integration. TPDDL (Tata Power Delhi Distribution Limited) EV tariff is considered for the base case scenario, while for SCN 1, SCN 2, and SCN 3, a rebate in the solar period is considered to encourage the shift of EV charging demand.

Figure 30: Cost to serve assumptions



²⁷ Please note that in the report and model we are not including or considering societal costs such as impact on air quality, health etc.

Figure 31: EV tariff assumptions²⁸


4.4.3 Inputs: Charging demand estimation

The cost of charging an electric freight vehicle can vary depending on the time of day and the energy demand in the area and the driving and stoppage pattern of the freight vehicle. This is where the concept of ‘smart charging’ and ToD comes into play. Smart charging is a system that allows electric vehicles to be charged at times when the demand for energy is low, and the cost to charge is also low. This helps to reduce the overall cost of charging while also benefiting the utility. In other words, when the difference between the cost to charge an electric vehicle and the average cost to serve is negative or very low, the utility benefits are also lower. Overall, smart charging as a concept can be used helping to reduce the cost of charging electric vehicles while also benefiting the utility company. By encouraging people to charge their electric vehicles during periods of low demand and low energy costs, everyone can benefit from the cost savings and reduced environmental impact of electric vehicles.

Table 7: Charging demand

Sum of power demand				
Row Labels	Fast	Overnight	Ultrafast	Grand Total
2023	8040	6508	0	14548
2025	12120	8780	0	20900
2027	32280	21028	0	53308

²⁸ In Mumbai, thermal storage systems are installed in DF programs to provide demand flexibility. The incentive offered by DISCOM was INR 1 per kWh. In the model, incentives are set at INR 0.5, 1, and 1.5 for scenarios 1, 2, and 3, respectively. We assume that higher incentives will lead to higher consumer participation .

2030	81240	70528	70500	222268
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Source: RAP, ICCT (October 2024), Optimising electric heavy duty truck charging on freight corridors in India

Charging Demand Estimation (CDE) for Case 1 and Charging Demand Estimation (CDE) for Case 2 are made for the case of depot charging to understand if for Case 1 charging is happening in a continuous slot as per ICCT assumptions³ and Case 2 according to from our understanding of the traffic count data case 2 is considered traffic count analysis and data was used to identify the slots where the traffic is moving the least assuming that that is the time parking is happening in the Delhi - Jaipur corridor.

Figure 32: Case 1, Fast + ultrafast charging demand, 2023 to 2030

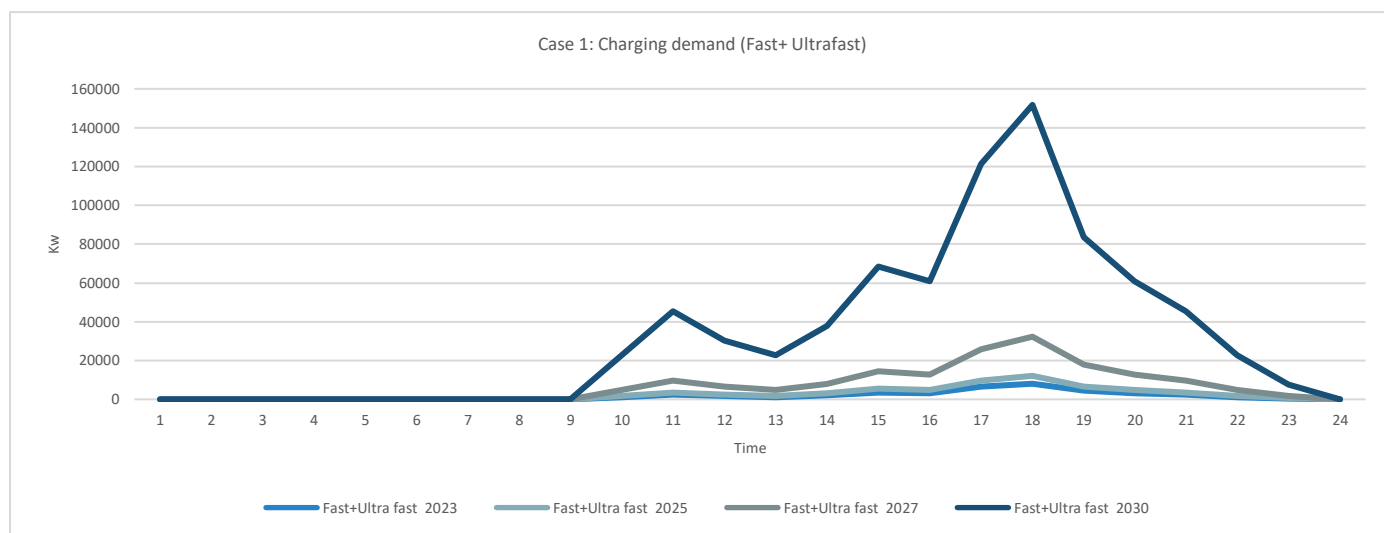


Figure 33: Case 1, Overnight charging demand, 2023 to 2030

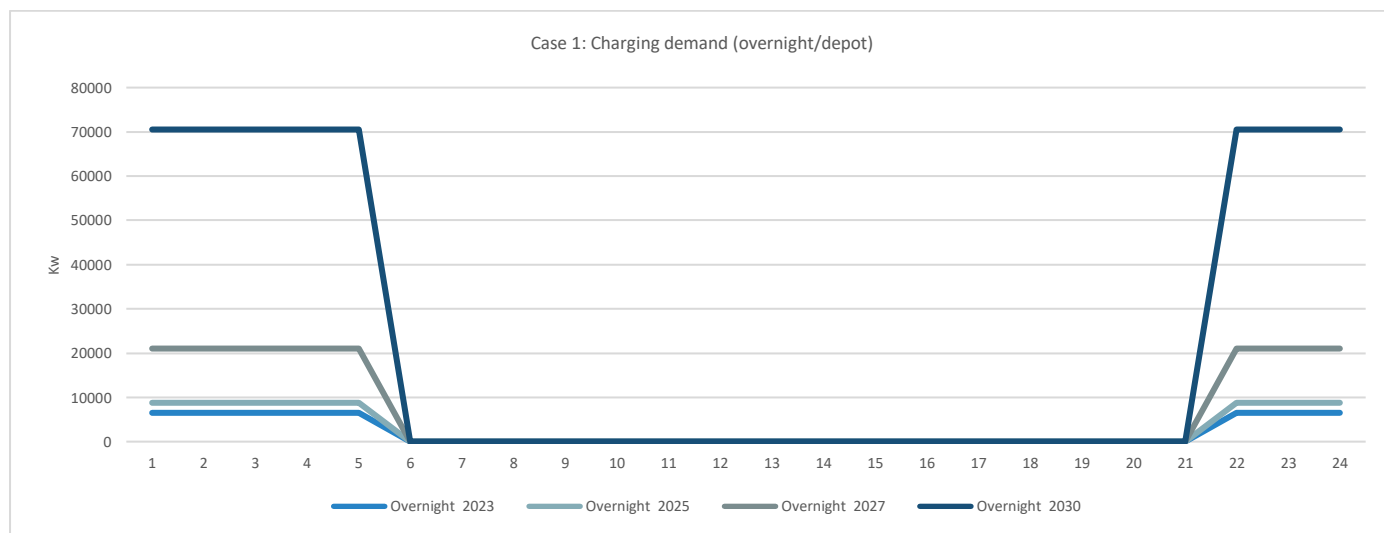


Figure 34: Case 1, Total charging demand, 2023 to 2030

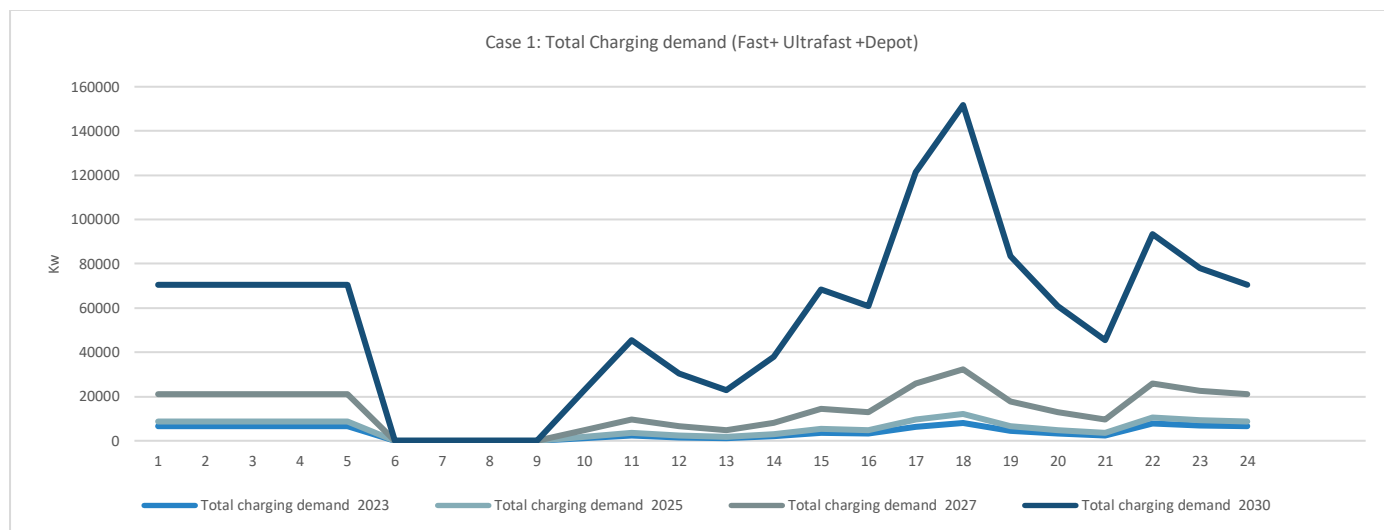


Figure 35: Case 2, Fast + ultrafast charging demand, 2023 to 2030

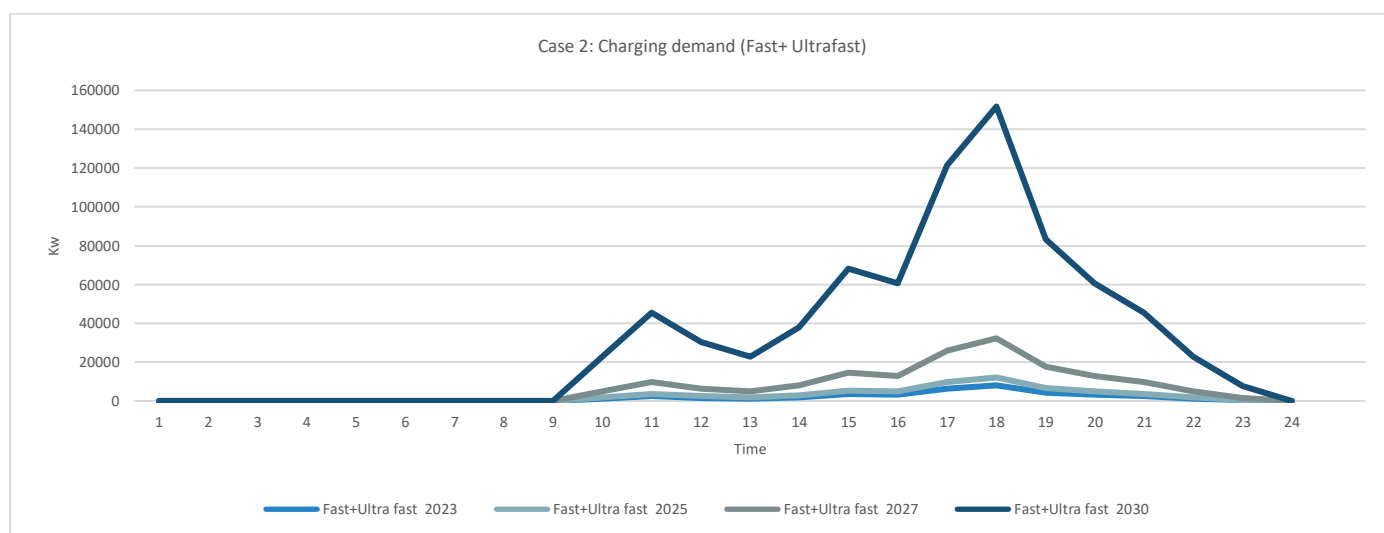


Figure 36: Case 2, overnight charging demand, 2023 to 2030

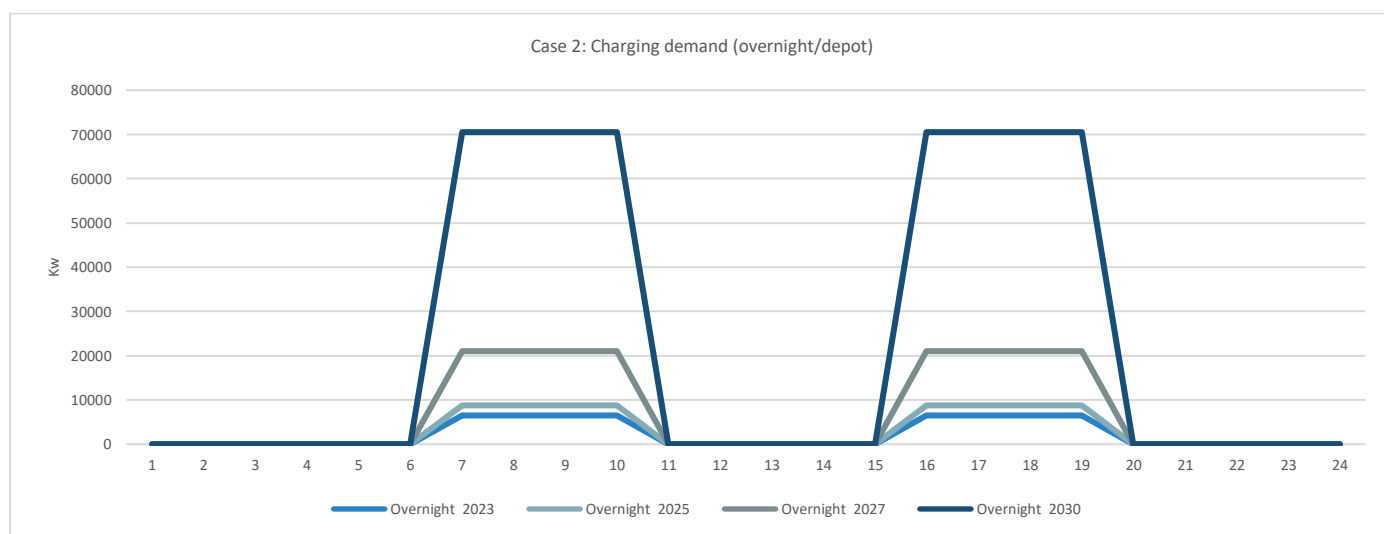
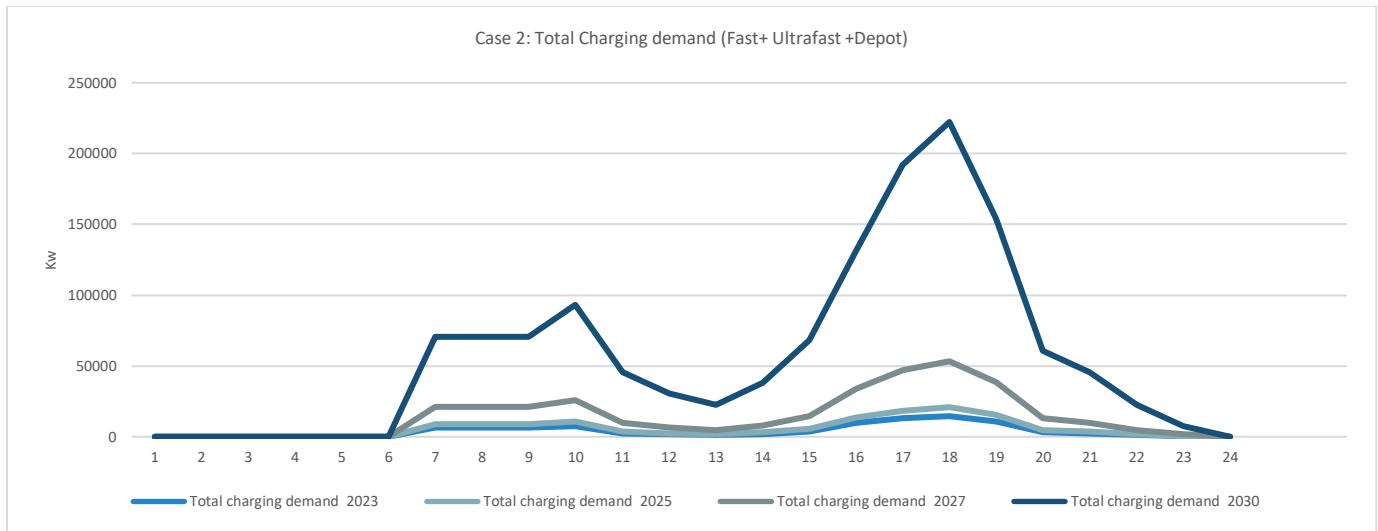


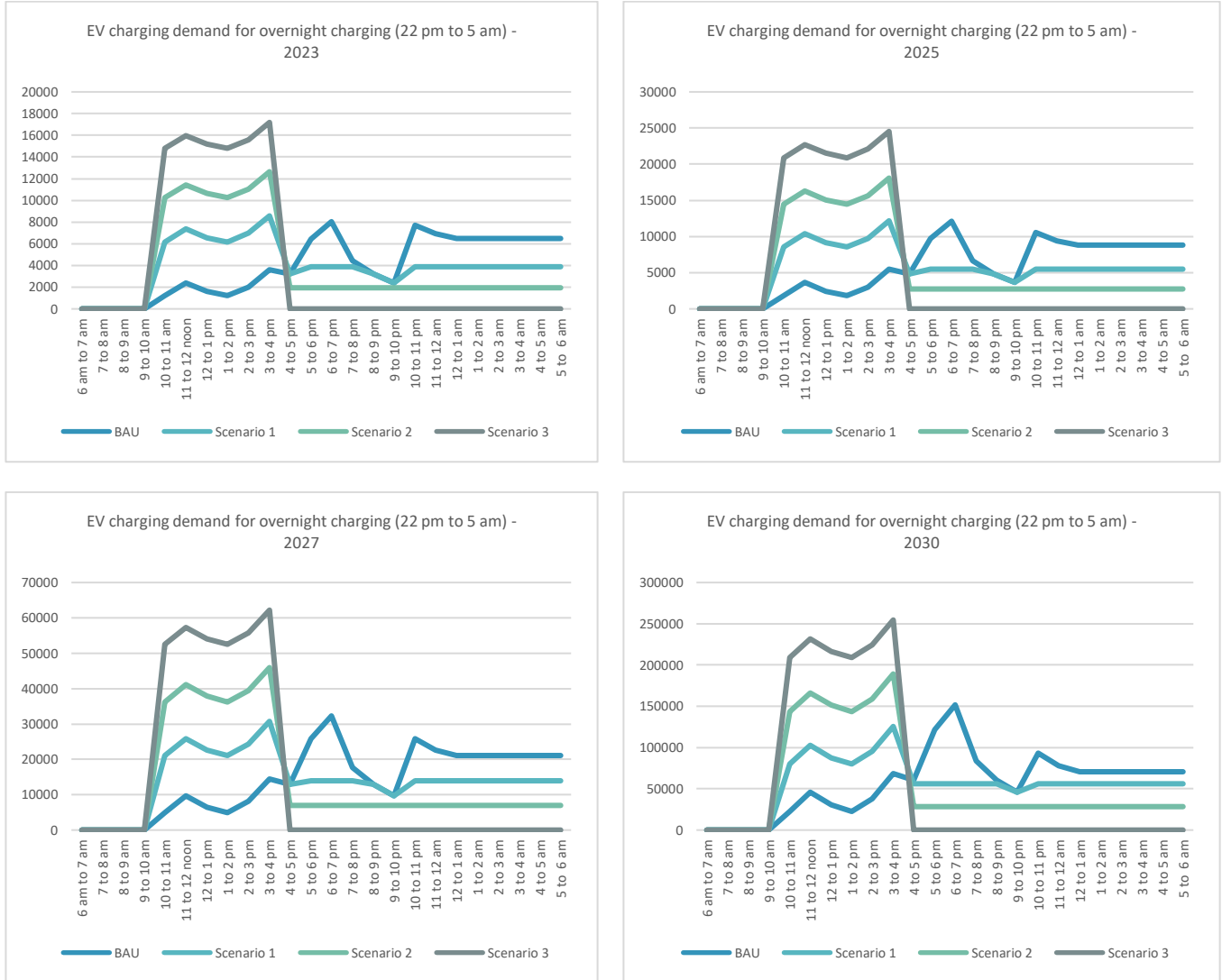
Figure 37: Case 2, Total charging demand, 2023 to 2030



4.5 Outputs

4.5.1 Case 1: Depot charging (Total charging demand and slot between 22:00 PM and 5:00 AM)²⁹

Figure 38: Case 1, Charging demand estimations- shifting to solar hours for 2023, 2025, 2027 & 2030



For Case 1, **APU for all the scenarios is better than the BAU scenarios in all the years considered.** For 2023 and 2025 scenario 2 gives the highest increase in APU change and for 2027 and 2030 scenario 3 shows the maximum profit. Shifting of charging demand in peak and night time has resulted in an increase in APU.

²⁹ Here the input is total charging demand from Case 1 and then this is shifted to solar hours according to scenario considerations, scenario 1, 2 and 3 respectively

Table 8: (APU) Average profit to utility case 1

APU (INR/day)	BAU	Scenario 1	Scenario 2	Scenario 3
2023	35248.38	93511.12	111951.7	109713.6
2025	61424.71	150542.4	190132.7	199814.1
2027	184842.5	423408.8	558164.7	614992.5
2030	1005654	1850151	2562391	2921462

Table 9: Case 1 | (A) Rebates to EV consumer for shifting demand (utility power sales in BAU - Utility sales in SCN) (B) Savings in utility generation costs (Utility generation cost in SCN - Utility generation costs in BAU) (C) Profit to utility (Savings in generation costs - Rebates) (D) Change in APU

Rebates to EV consumer for shifting demand (utility power sales in BAU - Utility sales in SCN)			
	Scenario 1	Scenario 2	Scenario 3
2023	16189	57999	128491
2025	23408	83137	183183
2027	60065	211605	463849
2030	259601	876706	1891577

(A)

Savings in utility generation costs (Utility generation cost in SCN - Utility generation costs in BAU)			
	Scenario 1	Scenario 2	Scenario 3
2023	74451	134702	202956
2025	112525	211845	321572
2027	298631	584928	893999
2030	1104097	2433442	3807385

(B)

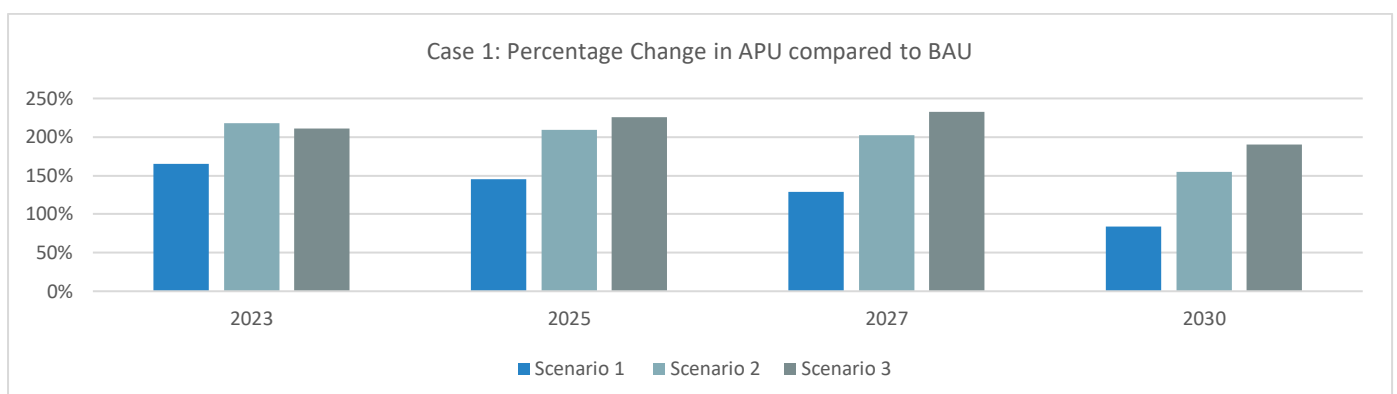
Profit to utility (Savings in generation costs - Rebates)			
	Scenario 1	Scenario 2	Scenario 3
2023	58263	76703	74465
2025	89118	128708	138389
2027	238566	373322	430150
2030	844496	1556736	1915808

(C)

Change in APU			
	Scenario 1	Scenario 2	Scenario 3
2023	165%	218%	211%
2025	145%	210%	225%
2027	129%	202%	233%
2030	84%	155%	191%

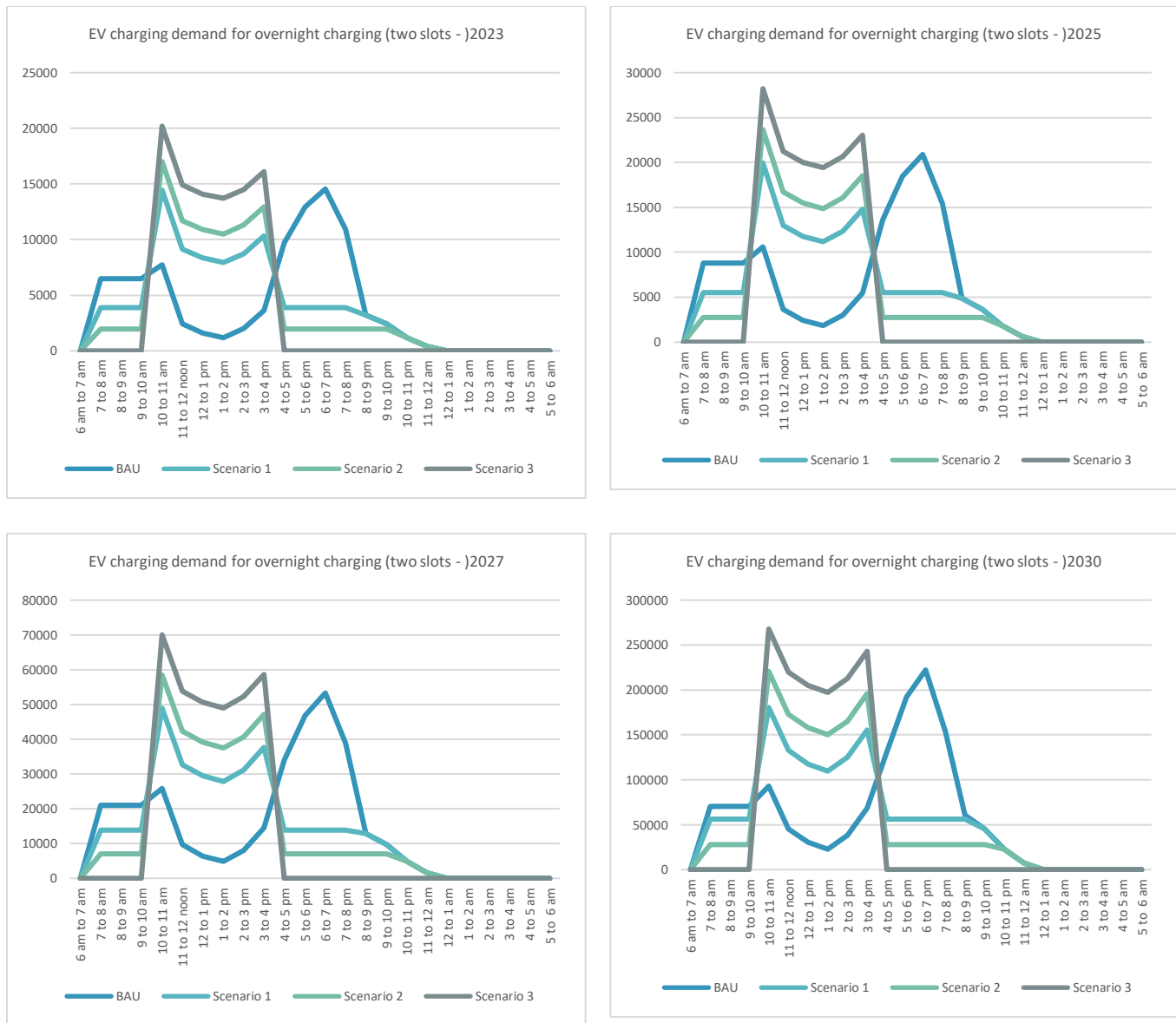
(D)

Figure 39: Case 1: Percentage Change in APU compared to BAU



4.5.2 Case 2: Depot charging happening between two slots from 7:00 AM to 10:00 AM & 4:00 PM to 7:00 PM

Figure 40: Case 2, charging demand estimations- shifting to solar hours for 2023, 2025, 2027 & 2030



For Case 2, SCN 2 can result in negative change in APU compared to BAU scenario. So the shifting of all the demand to solar hours might not be feasible from utilities perspective.

Table 10: Average profit to utility Case 2

APU (INR/day)	BAU	Scenario 1	Scenario 2	Scenario 3
2023	136163.5	161804.3	138473.2	107468.5
2025	200790.8	255713.6	231644.6	197088.1
2027	526336.1	709534.8	672301.9	609189.1
2030	2176896	3077948	3049926	2904431

Table 11: Case 2 | (A) Rebates to EV consumer for shifting demand (utility power sales in BAU - Utility sales in SCN) (B) Savings in utility generation costs (Utility generation cost in SCN - Utility generation costs in BAU) (C) Profit to utility (Savings in generation costs - Rebates) (D) Change in APU

Rebates to EV consumer for shifting demand (utility power sales in BAU - Utility sales in SCN)			
	Scenario 1	Scenario 2	Scenario 3
2023	33014	80493	148991
2025	45920	113483	210840
2027	113505	284279	530087
2030	430145	1120386	2113740

(A)

Savings in utility generation costs (Utility generation cost in SCN - Utility generation costs in BAU)			
	Scenario 1	Scenario 2	Scenario 3
2023	58655	82803	120296
2025	100843	144336	207137
2027	296703	430244	612940
2030	1331196	1993416	2841275

(B)

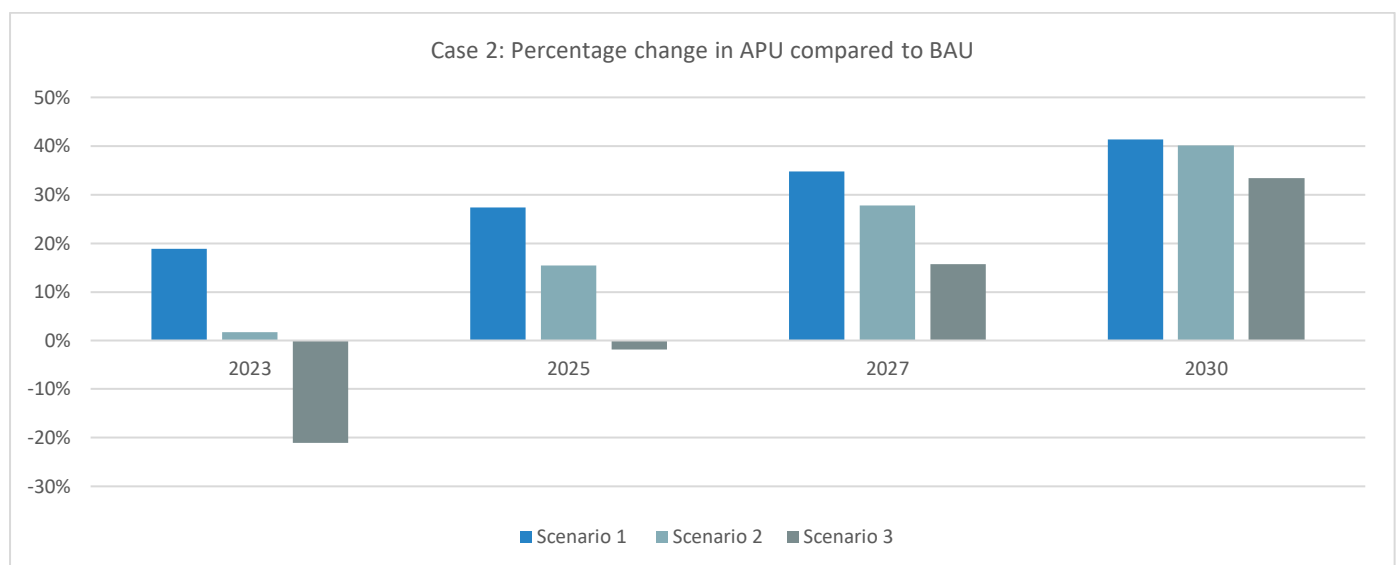
Profit to utility (Savings in generation costs - Rebates)			
	Scenario 1	Scenario 2	Scenario 3
2023	25641	2310	-28695
2025	54923	30854	-3703
2027	183199	145966	82853
2030	901052	873030	727534

(C)

Change in APU			
	Scenario 1	Scenario 2	Scenario 3
2023	19%	2%	-21%
2025	27%	15%	-2%
2027	35%	28%	16%
2030	41%	40%	33%

(D)

Figure 41: Case 2: Percentage change in APU compared to BAU



4.5.3 Estimating avoided GHG emissions for the 2 cases:

The calculation of savings in greenhouse gas (GHG) emissions involves considering the shift of EV charging loads to solar hours³⁰. This shift results in increased absorption of RE generation by the grid, replacing conventional fossil fuel-based generators³¹. The emission factor for the Indian power sector in the year 2022 was estimated to be 0.809 tons/MWh of energy generated³². For our calculations, we determined the extent to which EV charging loads were shifted to RE periods compared to the baseline scenario. The total GHG savings are then calculated by multiplying the energy shift by the grid emission factor. Greater shift to solar periods across various scenarios, coupled with increased EV penetration over time, leads to greater savings in GHG emissions as shown in figure below.

Calculation: EV charging demand shifted in solar hours (kWh/day)³³

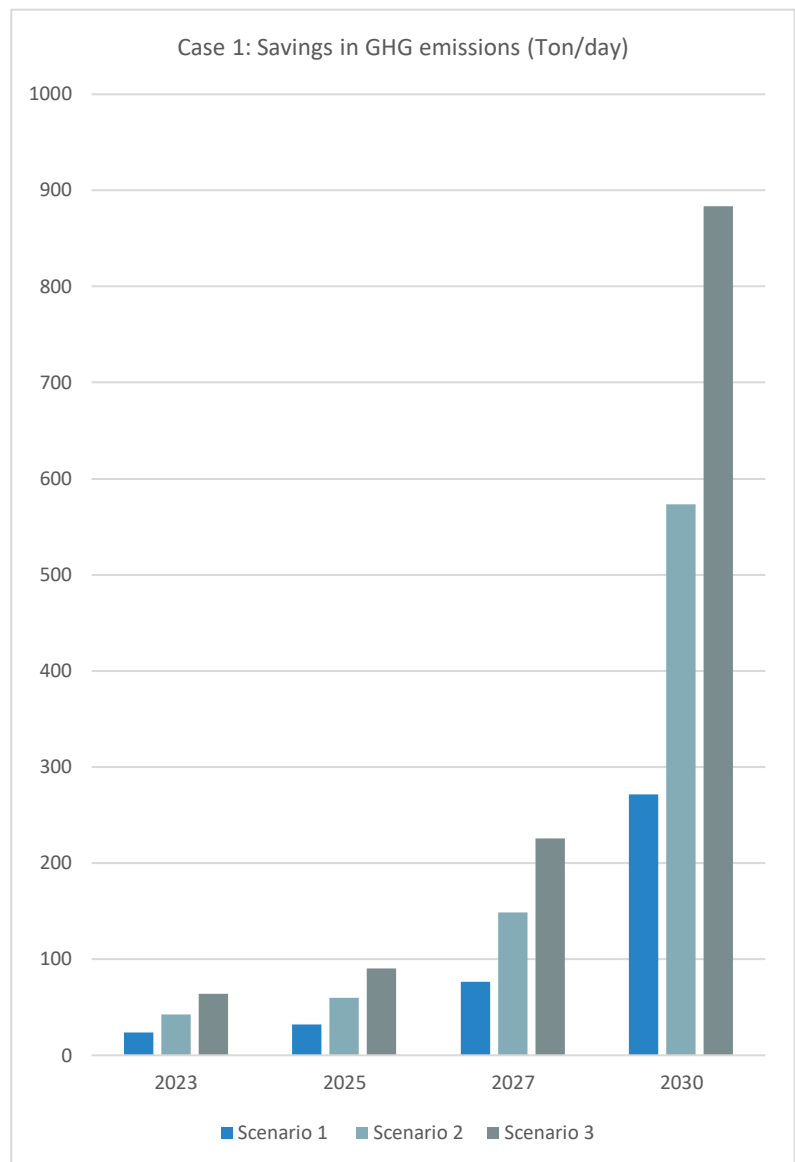
For case 1

Table 12: Case 1| EV charging demand shifted in solar hours (kWh/day)

EV charging demand shifted in solar hours (kWh/day) (Case 1)			
	Scenario 1	Scenario 2	Scenario 3
2023	29725.6	54147.9	81410
2025	40344.4	75786.1	114478
2027	97241.1	188493	286046
2030	343640	725584	1118075

Table 13: Case 1| Savings in GHG emission (Considering if RE plants are built but due to low demand, RE generation is curtailed) (Tons/day)

Savings in GHG emission (Considering if RE plants are built but due to low demand, RE generation is curtailed) (Tons/day)			
	Scenario 1	Scenario 2	Scenario 3
2023	23	43	64
2025	32	60	90
2027	77	149	226
2030	271	573	883



³⁰ Considering if RE plants are built but due to low demand, RE generation is curtailed

³¹ The assumption is that without the adjustment in EV consumption patterns, this solar energy would have been surplus and unused in other sectors of the economy.

³² CEA, https://cea.nic.in/wp-content/uploads/baseline/2023/01/Approved_report_emission_2021_22.pdf.

³³ Grid emission factor 0.79kg/KWh

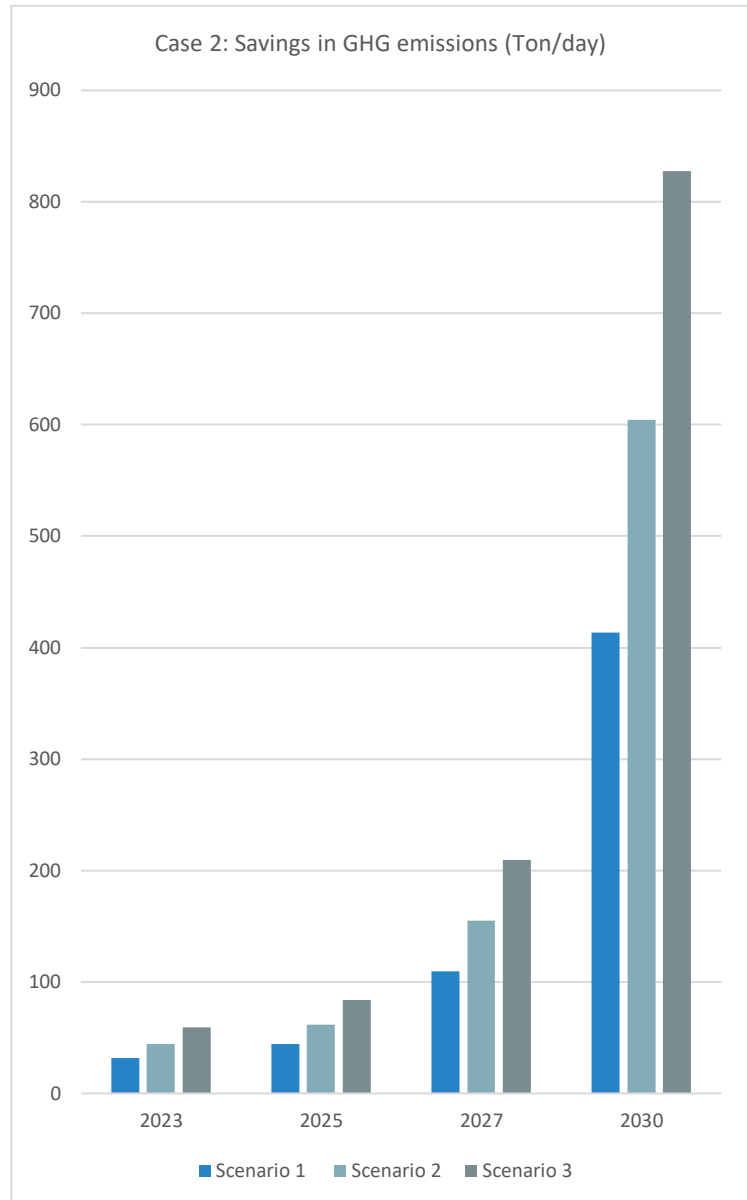
For case 2:

Table 14: Case2| EV charging demand shifted in solar hours (kWh/day)

EV charging demand shifted in solar hours (kWh/day) (Case 2)			
	Scenario 1	Scenario 2	Scenario 3
2023	40403.9	55768.4	74902
2025	56098.1	78400.6	105698
2027	138413	195850	265018
2030	523115	764883	1047547

Table 15: Case 2| Savings in GHG emission (Considering if RE plants are built but due to low demand, RE generation is curtailed) (Tons/day)

Savings in GHG emission (Considering if RE plants are built but due to low demand, RE generation is curtailed) (Tons/day)			
	Scenario 1	Scenario 2	Scenario 3
2023	32	44	59
2025	44	62	84
2027	109	155	209
2030	413	604	828



4.6. Interpretation of results

Case 1 and **Case 2** exhibit distinct patterns in the change in APU. In Case 1, the change in APU is consistently positive across all scenarios. However, in Case 2, the change in APU can be negative for certain scenarios. Despite the charging pattern for opportunity charging being the same for both cases, the difference in results can be attributed to the different charging patterns for depot charging.

In Case 1, there is a consistent positive change in APU across all scenarios and years. This is attributed to the fact that the depot charging demand occurs during the night hours, typically between 22:00 PM to 6:00 AM, when the average cost to serve is higher at around 6 INR/kWh.

In Case 2, the depot charging demand peaks during two slots, 7:00 AM to 11:00 AM and 4:00 PM to 8:00 PM, with an average cost to serve of 4.6 INR/kWh. The effectiveness of shifting EV charging loads to solar hours depends on the incentive offered to consumers and the cost savings achieved in cost to serve. In Case 1, where the average cost to serve during the shifted demand hours is higher compared to Case 2, implementing ToD for shifting demand to solar hours is more favourable.

4.6.2 Summary from the modelling exercise in context of the research question

If the demand were shifted to non-solar hours, the model could be adjusted to assess the cost implications and to change tariff rates and offer rebates accordingly. This analysis helps establish a comprehensive understanding of the cost and connection between increased charging demand for utilities, the effect of tariff rebates, and the expense of procured power, a holistic approach is necessary.

In case the off peak period and solar generation period coincides by incentivizing consumers to shift their electricity usage to off-peak solar hours, DISCOMs can reduce the strain on the electricity grid during peak hours and maximize the use of solar energy. This not only benefits the environment by reducing reliance on non-renewable energy sources but also reduces energy costs for consumers.

However, in order to effectively incentivize consumers to shift their electricity usage, there needs to be an understanding of the price elasticity of demand for shifting freight EV charging demand in the solar period. This requires a detailed analysis of consumer behaviour and preferences, as well as an examination of the potential benefits and costs associated with shifting electricity usage.

Once this analysis has been conducted, DISCOMs can offer rebates or other incentives to encourage consumers to shift their electricity usage to off-peak solar hours. This will ultimately result in an increase in DISCOMs profit, while also contributing to the overall goal of reducing reliance on non-renewable energy sources and promoting sustainable energy practices. Higher efficacy and utilisation factor of the existing power generation plants and as such we are for the purpose of the deli case study we have explored both the options.

Different Indian cities encounter specific challenges in harnessing solar power, primarily related to aligning solar hours with peak electricity demand. Some cities can integrate solar energy effectively, while others face constraints due to demand profile constraints and grid capacity issues. Therefore a single standardized approach cannot be adopted in every city.

To mitigate this, careful planning is crucial, involving the installation of energy storage systems like batteries and implementing demand-side management strategies. Additionally, social and economic barriers, such as financial constraints and lack of awareness, and unpredictable driving pattern in case of freight play a major role.

4.7 Limitations identified from model analysis and study

Limitations of model analysis

- This data does not capture variations due to seasonality
- Unavailability of data on price elasticity of demand, hence unclear if assumed rebates are adequate to stimulate envisaged shift in demand
- GHG emissions calculated are based on CEA data
- Uncertainty about likely demand needs and patterns

Limitations of RE integration in freight EV charging and smart charging in the Indian context:

1. Freight EV charging scenario in India:

- **Limited adoption of electric freight vehicles:** As of now, there is limited official adoption of electric freight vehicles in India. The lack of a substantial fleet of electric freight vehicles poses a challenge for the development of dedicated freight EV charging infrastructure.
- **Challenges in charging infrastructure development:** The absence of a significant number of electric freight vehicles results in a slower pace of dedicated freight charging infrastructure development. Investments and incentives may be required to encourage the adoption of electric freight vehicles.

2. Battery technology and range limitations:

- The current state of battery technology imposes limitations on the range and capacity of electric vehicles (EVs), especially for freight vehicles. Limited range may impact the feasibility of long-haul freight operations without frequent recharging.

3. Inconsistent solar generation and EV charging patterns:

- The intermittent nature of RE generation and the varying charging patterns of EVs, including freight vehicles, pose challenges for smart charging optimization. Coordinating the charging of EVs with RE generation peaks requires additional oversight in the Indian context.

4. Peak load addition and freight driving patterns:

- Freight vehicles often follow driving patterns, which may or may not coincide with peak solar hours. If a significant number of electric freight vehicles charge simultaneously during these hours, it can lead to an **additional peak load on the grid, challenging grid stability.**

5. Storage solutions and grid upgrades:

- Storage solutions, such as advanced battery technologies, may be necessary to address the mismatch between RE generation and freight EV charging patterns. Additionally, grid upgrades may be needed to accommodate the increased load during peak charging periods.

Overall, while the integration of RE with freight EV charging holds great potential for sustainable transportation in India, addressing the current limitations requires coordinated efforts from policymakers, industry stakeholders, and technology providers. Overcoming these challenges will pave the way for a more efficient and environmentally friendly freight transportation system in the country.

Chapter 5: General inferences from the study

There are several factors that need to be considered for the successful implementation of charging for freight vehicles. The behaviour and driving pattern of truck drivers, as most of the decisions are up to the discretion of the truck driver. The movement of freight vehicles, routes taken, rest stops and durations in solar hours, which are affected by requirements of the trucking company, government regulations on hours of driving etc.

This is because most vehicle movement occurs during the day, which coincides with the solar period. Therefore, it is essential to ensure that there are sufficient parking spaces equipped with chargers to facilitate the charging of these vehicles during the day. This limitation also highlights the lack of proper infrastructure for driver stay and accommodation. Currently, there is no uptake of electric vehicles in the freight segment in India. It is challenging to establish the driving and parking patterns of electric trucks because their usage can significantly differ from that of diesel and CNG trucks.

One approach to overcome this limitation can be the use of wind power as a substitute for RE (solar) for usage at night. The use of wind power comes with its own set of limitations but can be explored as a complement which can help to ensure that there is a continuous supply of renewable energy for these vehicles, even during the night. However, **the effectiveness of shifting the charging from night to solar slots by offering incentives/rebates has its limitations when operating traffic's peak working hours coincide with the solar period.** Therefore, it is essential to consider the practicality and feasibility of such measures in the context of local traffic patterns and working hours.

Additionally, when evaluating the realistic implementation of any scenario based on the drivers' patterns identified in the survey, several key considerations come into play. The survey indicates that the main movements tend to occur at night, with stoppages are random and does not follow a specific pattern. The average duration of stoppage is found to be between 30 minutes to 1 hour, and these stoppages are at the complete discretion of the driver, depending on the final destination of the goods being delivered. Given these patterns, the feasibility of implementing smart charging strategies should be assessed in light of the drivers' behaviours. Night-time movements suggest an opportunity for overnight charging, but the random and discretionary nature of stoppages poses challenges. Smart charging solutions must be designed to accommodate these variations in stoppage patterns and ensure that charging infrastructure is conveniently accessible during these periods.

Further the study allows us to draw broad insights as follows:

- Smart EV charging can unlock value by adjusting demand in line with solar penetration, especially in contexts where overall electricity demand lacks sophistication. Minimizing the associated costs requires careful planning and strategy.
- Smart charging for EVs becomes crucial for effective integration of RE in grid. The importance of smart tariffs across various demand segments influences this. Introducing smart tariffs for EVs can be particularly impactful where such strategies are lacking in other sectors.
- The cost-saving benefits can be shared between DISCOMs and consumers based on tariff adjustments by DISCOMs.
- EV charging has a relatively minor impact on the grid and therefore grid savings do not appear to be the main driver of value offered by smart charging

Summarising, our analysis of case studies has revealed that ToD pricing strategies can effectively manage EV charging demand. Furthermore, our model has explored various scenarios to assess the impact of shifting EV charging demand to solar hours on DISCOMs profitability. It is crucial to conduct a detailed evaluation of local traffic patterns when considering the feasibility of adjusting parking times to align with solar availability. Moreover, the successful implementation of smart charging scenarios hinges on accommodating diverse and optional stopping patterns, underscoring the importance of adaptable and user-friendly solutions. This underscores the importance of thoroughly examining freight drivers' behaviour, vehicle movement patterns, and the integration of different renewable energy

sources with DISCOMs. Addressing these factors is essential for developing a more sustainable and environmentally conscious freight transportation system.

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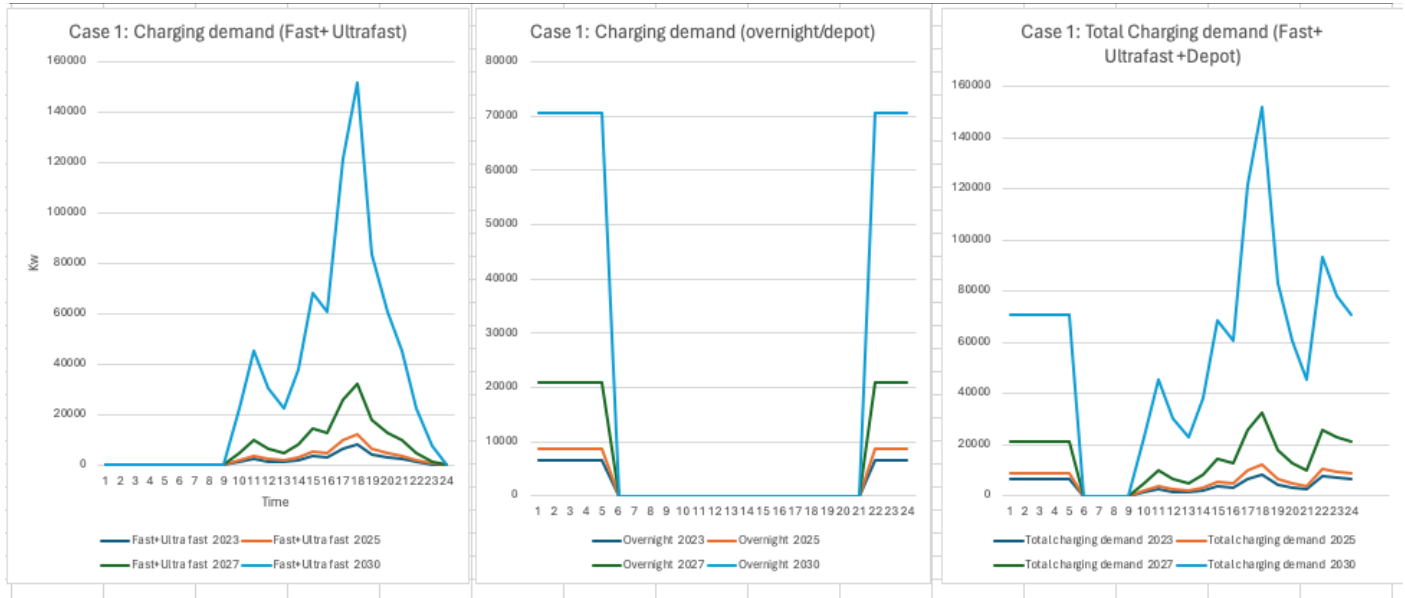
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Annexure 1: 24 hour charging demand profile

Charging profile: number of charger and utilisation for 24 hour profile

Number of chargers on hourly basis			% utilisation of chargers (% utilisation is calculated by considering for slots with maximum vehicles utilisation is 100%)		
Hours	Number of trucks Fast charging	Number of trucks Ultrafast charging	Hours	% utilisation- Fast charging	% utilisation- Ultrafast charging
1	0	0	1	0	0
2	0	0	2	0	0
3	0	0	3	0	0
4	0	0	4	0	0
5	0	0	5	0	0
6	0	0	6	0	0
7	0	0	7	0	0
8	0	0	8	0	0
9	3	0	9	0.075	0
10	3	3	10	0.075	0.15
11	8	6	11	0.2	0.3
12	6	4	12	0.15	0.2
13	6	3	13	0.15	0.15
14	11	5	14	0.275	0.25
15	17	9	15	0.425	0.45
16	17	8	16	0.425	0.4
17	28	16	17	0.7	0.8
18	40	20	18	1	1
19	40	11	19	1	0.55
20	23	8	20	0.575	0.4
21	23	6	21	0.575	0.3
22	7	3	22	0.175	0.15
23	3	1	23	0.075	0.05
24	3	0	24	0.075	0

Case 1: Charging demand														
	Fast+Ultra fast					Overnight					Total charging demand			
	2023	2025	2027	2030		2023	2025	2027	2030		2023	2025	2027	2030
1	0	0	0	0	1	6508	8780	21028	70528	1	6508	8780	21028	70528
2	0	0	0	0	2	6508	8780	21028	70528	2	6508	8780	21028	70528
3	0	0	0	0	3	6508	8780	21028	70528	3	6508	8780	21028	70528
4	0	0	0	0	4	6508	8780	21028	70528	4	6508	8780	21028	70528
5	0	0	0	0	5	6508	8780	21028	70528	5	6508	8780	21028	70528
6	0	0	0	0	6	0	0	0	0	6	0	0	0	0
7	0	0	0	0	7	0	0	0	0	7	0	0	0	0
8	0	0	0	0	8	0	0	0	0	8	0	0	0	0
9	0	0	0	0	9	0	0	0	0	9	0	0	0	0
10	1206	1818	4842	22761	10	0	0	0	0	10	1206	1818	4842	22761
11	2412	3636	9684	45522	11	0	0	0	0	11	2412	3636	9684	45522
12	1608	2424	6456	30348	12	0	0	0	0	12	1608	2424	6456	30348
13	1206	1818	4842	22761	13	0	0	0	0	13	1206	1818	4842	22761
14	2010	3030	8070	37935	14	0	0	0	0	14	2010	3030	8070	37935
15	3618	5454	14526	68283	15	0	0	0	0	15	3618	5454	14526	68283
16	3216	4848	12912	60696	16	0	0	0	0	16	3216	4848	12912	60696
17	6432	9696	25824	121392	17	0	0	0	0	17	6432	9696	25824	121392
18	8040	12120	32280	151740	18	0	0	0	0	18	8040	12120	32280	151740
19	4422	6666	17754	83457	19	0	0	0	0	19	4422	6666	17754	83457
20	3216	4848	12912	60696	20	0	0	0	0	20	3216	4848	12912	60696
21	2412	3636	9684	45522	21	0	0	0	0	21	2412	3636	9684	45522
22	1206	1818	4842	22761	22	6508	8780	21028	70528	22	7714	10598	25870	93289
23	402	606	1614	7587	23	6508	8780	21028	70528	23	6910	9386	22642	78115
24	0	0	0	0	24	6508	8780	21028	70528	24	6508	8780	21028	70528



Case 2: Charging demand														
	Fast+Ultra fast					Overnight					Total charging demand			
	2023	2025	2027	2030		2023	2025	2027	2030		2023	2025	2027	2030
1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
2	0	0	0	0	2	0	0	0	0	2	0	0	0	0
3	0	0	0	0	3	0	0	0	0	3	0	0	0	0
4	0	0	0	0	4	0	0	0	0	4	0	0	0	0
5	0	0	0	0	5	0	0	0	0	5	0	0	0	0
6	0	0	0	0	6	0	0	0	0	6	0	0	0	0
7	0	0	0	0	7	6508	8780	21028	70528	7	6508	8780	21028	70528
8	0	0	0	0	8	6508	8780	21028	70528	8	6508	8780	21028	70528
9	0	0	0	0	9	6508	8780	21028	70528	9	6508	8780	21028	70528
10	1206	1818	4842	22761	10	6508	8780	21028	70528	10	7714	10598	25870	93289
11	2412	3636	9684	45522	11	0	0	0	0	11	2412	3636	9684	45522
12	1608	2424	6456	30348	12	0	0	0	0	12	1608	2424	6456	30348
13	1206	1818	4842	22761	13	0	0	0	0	13	1206	1818	4842	22761
14	2010	3030	8070	37935	14	0	0	0	0	14	2010	3030	8070	37935
15	3618	5454	14526	68283	15	0	0	0	0	15	3618	5454	14526	68283
16	3216	4848	12912	60696	16	6508	8780	21028	70528	16	9724	13628	33940	131224
17	6432	9696	25824	121392	17	6508	8780	21028	70528	17	12940	18476	46852	191920
18	8040	12120	32280	151740	18	6508	8780	21028	70528	18	14548	20900	53308	222268
19	4422	6666	17754	83457	19	6508	8780	21028	70528	19	10930	15446	38782	153985
20	3216	4848	12912	60696	20	0	0	0	0	20	3216	4848	12912	60696
21	2412	3636	9684	45522	21	0	0	0	0	21	2412	3636	9684	45522
22	1206	1818	4842	22761	22	0	0	0	0	22	1206	1818	4842	22761
23	402	606	1614	7587	23	0	0	0	0	23	402	606	1614	7587
24	0	0	0	0	24	0	0	0	0	24	0	0	0	0



Annexure 2: Solar shifting

Estimation of Average cost to serve, average cost to charge and Average profit to utility for BAU for Case 1

BAU		Shift to solar hours					Tariff for EV charging load				
Time slots	2023	2023 BAU	SCN 1	SCN 2	SCN 3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3	
6 am to 7 am	0	0	0	0	0	4.980238417	6.45	6.45	6.45	6.45	
7 to 8 am	0	0	0	0	0	4.77582975	6.45	6.45	6.45	6.45	
8 to 9 am	0	0	0	0	0	4.361875473	6.45	6.45	6.45	6.45	
9 to 10 am	0	0	0	0	0	3.774376774	6.45	6.45	6.45	6.45	
10 to 11 am	1206	1206	6160.26	10230.7	14774.3	3.668145161	6	5.5	5	4.5	
11 to 12 noon	2412	2412	7366.26	11436.7	15980.3	3.526051694	6	5.5	5	4.5	
12 to 1 pm	1608	1608	6562.26	10632.7	15176.3	3.269597258	6	5.5	5	4.5	
1 to 2 pm	1206	1206	6160.26	10230.7	14774.3	3.082774113	6	5.5	5	4.5	
2 to 3 pm	2010	2010	6964.26	11034.7	15578.3	2.903862742	6	5.5	5	4.5	
3 to 4 pm	3618	3618	8572.26	12642.7	17186.3	3.488572742	6	5.5	5	4.5	
4 to 5 pm	3216	3216	3216	1947.29	0	4.10220629	6	6	6	6	
5 to 6 pm	6432	6432	3894.58	1947.29	0	4.701368629	6	6	6	6	
6 to 7 pm	8040	8040	3894.58	1947.29	0	5.022339677	6	6	6	6	
7 to 8 pm	4422	4422	3894.58	1947.29	0	5.576757097	6	6	6	6	
8 to 9 pm	3216	3216	3216	1947.29	0	7.278916613	6	6	6	6	
9 to 10 pm	2412	2412	2412	1947.29	0	6.554156452	6	6	6	6	
10 to 11 pm	7714	7714	3894.58	1947.29	0	6.922576694	6	6	6	6	
11 to 12 am	6910	6910	3894.58	1947.29	0	7.126923952	6	6	6	6	
12 to 1 am	6508	6508	3894.58	1947.29	0	7.048557419	6	6	6	6	
1 to 2 am	6508	6508	3894.58	1947.29	0	6.81089875	6	6	6	6	
2 to 3 am	6508	6508	3894.58	1947.29	0	5.863105583	5.55	5.55	5.55	5.55	
3 to 4 am	6508	6508	3894.58	1947.29	0	5.179784333	5.55	5.55	5.55	5.55	
4 to 5 am	6508	6508	3894.58	1947.29	0	4.714516583	5.55	5.55	5.55	5.55	
5 to 6 am	6508	6508	3894.58	1947.29	0	4.67285575	5.55	5.55	5.55	5.55	
Average demand	3894.58	Sum of shifted demand	29725.6	54147.9	81410	Average profit to utility 2023 = [(EV tariff - Cost to serve) x Charging demand]					
							35248.38	93511.12	111951.7	109713.6	

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2025 for case 1

	2025	2025 BAU	SCN 1	SCN 2	SCN3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	0	7 to 8 am	0	0	0	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	0	8 to 9 am	0	0	0	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	0	9 to 10 am	0	0	0	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	1818	10 to 11 am	1818	8542.07	14449	3.301330645	6	5.5	5	4.5
11 to 12 noon	3636	11 to 12 noon	3636	10360.1	16267	3.173446524	6	5.5	5	4.5
12 to 1 pm	2424	12 to 1 pm	2424	9148.07	15055	2.942637532	6	5.5	5	4.5
1 to 2 pm	1818	1 to 2 pm	1818	8542.07	14449	2.774496702	6	5.5	5	4.5
2 to 3 pm	3030	2 to 3 pm	3030	9754.07	15661	2.613476468	6	5.5	5	4.5
3 to 4 pm	5454	3 to 4 pm	5454	12178.1	18085	3.139715468	6	5.5	5	4.5
4 to 5 pm	4848	4 to 5 pm	4848	4848	2763.71	4.10220629	6	6	6	6
5 to 6 pm	9696	5 to 6 pm	9696	5527.42	2763.71	4.701368629	6	6	6	6
6 to 7 pm	12120	6 to 7 pm	12120	5527.42	2763.71	5.022339677	6	6	6	6
7 to 8 pm	6666	7 to 8 pm	6666	5527.42	2763.71	5.576757097	6	6	6	6
8 to 9 pm	4848	8 to 9 pm	4848	4848	2763.71	7.278916613	6	6	6	6
9 to 10 pm	3636	9 to 10 pm	3636	3636	2763.71	6.554156452	6	6	6	6
10 to 11 pm	10598	10 to 11 pm	10598	5527.42	2763.71	6.922576694	6	6	6	6
11 to 12 am	9386	11 to 12 am	9386	5527.42	2763.71	7.126923952	6	6	6	6
12 to 1 am	8780	12 to 1 am	8780	5527.42	2763.71	7.048557419	6	6	6	6
1 to 2 am	8780	1 to 2 am	8780	5527.42	2763.71	6.81089875	6	6	6	6
2 to 3 am	8780	2 to 3 am	8780	5527.42	2763.71	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	8780	3 to 4 am	8780	5527.42	2763.71	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	8780	4 to 5 am	8780	5527.42	2763.71	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	8780	5 to 6 am	8780	5527.42	2763.71	4.67285575	5.55	5.55	5.55	5.55
Average demand	5527.42	Sum of shifted demand	40344.4	75786.1	114478	Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]	61424.71	150542.4	190132.7	199814.1

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2027 for case 1

	2027	2027 BAU	SCN 1	SCN 2	SCN3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	0	7 to 8 am	0	0	0	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	0	8 to 9 am	0	0	0	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	0	9 to 10 am	0	0	0	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	4842	10 to 11 am	4842	21048.8	36257.6	2.934516129	6	5.5	5	4.5
11 to 12 noon	9684	11 to 12 noon	9684	25890.8	41099.6	2.820841355	6	5.5	5	4.5
12 to 1 pm	6456	12 to 1 pm	6456	22662.8	37871.6	2.615677808	6	5.5	5	4.5
1 to 2 pm	4842	1 to 2 pm	4842	21048.8	36257.6	2.46621929	6	5.5	5	4.5
2 to 3 pm	8070	2 to 3 pm	8070	24276.8	39485.6	2.323090194	6	5.5	5	4.5
3 to 4 pm	14526	3 to 4 pm	14526	30732.8	45941.6	2.790858194	6	5.5	5	4.5
4 to 5 pm	12912	4 to 5 pm	12912	12912	6968.04	4.10220629	6	6	6	6
5 to 6 pm	25824	5 to 6 pm	25824	13936.1	6968.04	4.701368629	6	6	6	6
6 to 7 pm	32280	6 to 7 pm	32280	13936.1	6968.04	5.022339677	6	6	6	6
7 to 8 pm	17754	7 to 8 pm	17754	13936.1	6968.04	5.576757097	6	6	6	6
8 to 9 pm	12912	8 to 9 pm	12912	12912	6968.04	7.278916613	6	6	6	6
9 to 10 pm	9684	9 to 10 pm	9684	9684	6968.04	6.554156452	6	6	6	6
10 to 11 pm	25870	10 to 11 pm	25870	13936.1	6968.04	6.922576694	6	6	6	6
11 to 12 am	22642	11 to 12 am	22642	13936.1	6968.04	7.126923952	6	6	6	6
12 to 1 am	21028	12 to 1 am	21028	13936.1	6968.04	7.048557419	6	6	6	6
1 to 2 am	21028	1 to 2 am	21028	13936.1	6968.04	6.81089875	6	6	6	6
2 to 3 am	21028	2 to 3 am	21028	13936.1	6968.04	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	21028	3 to 4 am	21028	13936.1	6968.04	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	21028	4 to 5 am	21028	13936.1	6968.04	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	21028	5 to 6 am	21028	13936.1	6968.04	4.67285575	5.55	5.55	5.55	5.55
Average demand	13936.1	Sum of shifted demand	97241.1	188493	286046	Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]	184842.5	423408.8	558164.7	614992.5

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2030 for case 1

2030	2030	BAU	SCN 1	SCN 2	SCN 3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	0	7 to 8 am	0	0	0	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	0	8 to 9 am	0	0	0	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	0	9 to 10 am	0	0	0	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	22761	10 to 11 am	22761	80034.4	143692	2.567701613	6	5.5	5	4.5
11 to 12 noon	45522	11 to 12 noon	45522	102795	166453	2.468236185	6	5.5	5	4.5
12 to 1 pm	30348	12 to 1 pm	30348	87621.4	151279	2.288718081	6	5.5	5	4.5
1 to 2 pm	22761	1 to 2 pm	22761	80034.4	143692	2.157941879	6	5.5	5	4.5
2 to 3 pm	37935	2 to 3 pm	37935	95208.4	158866	2.032703919	6	5.5	5	4.5
3 to 4 pm	68283	3 to 4 pm	68283	125556	189214	2.442000919	6	5.5	5	4.5
4 to 5 pm	60696	4 to 5 pm	60696	56070.2	28035.1	4.10220629	6	6	6	6
5 to 6 pm	121392	5 to 6 pm	121392	56070.2	28035.1	4.701368629	6	6	6	6
6 to 7 pm	151740	6 to 7 pm	151740	56070.2	28035.1	5.022339677	6	6	6	6
7 to 8 pm	83457	7 to 8 pm	83457	56070.2	28035.1	5.576757097	6	6	6	6
8 to 9 pm	60696	8 to 9 pm	60696	56070.2	28035.1	7.278916613	6	6	6	6
9 to 10 pm	45522	9 to 10 pm	45522	45522	28035.1	6.554156452	6	6	6	6
10 to 11 pm	93289	10 to 11 pm	93289	56070.2	28035.1	6.922576694	6	6	6	6
11 to 12 am	78115	11 to 12 am	78115	56070.2	28035.1	7.126923952	6	6	6	6
12 to 1 am	70528	12 to 1 am	70528	56070.2	28035.1	7.048557419	6	6	6	6
1 to 2 am	70528	1 to 2 am	70528	56070.2	28035.1	6.81089875	6	6	6	6
2 to 3 am	70528	2 to 3 am	70528	56070.2	28035.1	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	70528	3 to 4 am	70528	56070.2	28035.1	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	70528	4 to 5 am	70528	56070.2	28035.1	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	70528	5 to 6 am	70528	56070.2	28035.1	4.67285575	5.55	5.55	5.55	5.55
Average demand	56070.2	Sum of shifted demand	343640	725584	1118075	Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]	1005654	1850151	2562391	2921462

Estimation of Average cost to serve, average cost to charge and Average profit to utility for BAU for case 2

BAU	2023	2023	BAU	SCN 1	SCN 2	SCN 3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
Time slots			Charging demand shift to solar hours								
6 am to 7 am	0	6 am to 7 am	0	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	6508	7 to 8 am	6508	3894.58	1947.29	0	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	6508	8 to 9 am	6508	3894.58	1947.29	0	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	6508	9 to 10 am	6508	3894.58	1947.29	0	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	7714	10 to 11 am	7714	14448	17008.7	20197.7	3.668145161	6	5.5	5	4.5
11 to 12 noon	2412	11 to 12 noon	2412	9145.99	11706.7	14895.7	3.526051694	6	5.5	5	4.5
12 to 1 pm	1608	12 to 1 pm	1608	8341.99	10902.7	14091.7	3.269597258	6	5.5	5	4.5
1 to 2 pm	1206	1 to 2 pm	1206	7939.99	10500.7	13689.7	3.082774113	6	5.5	5	4.5
2 to 3 pm	2010	2 to 3 pm	2010	8743.99	11304.7	14493.7	2.903862742	6	5.5	5	4.5
3 to 4 pm	3618	3 to 4 pm	3618	10352	12912.7	16101.7	3.488572742	6	5.5	5	4.5
4 to 5 pm	9724	4 to 5 pm	9724	3894.58	1947.29	0	4.10220629	6	6	6	6
5 to 6 pm	12940	5 to 6 pm	12940	3894.58	1947.29	0	4.701368629	6	6	6	6
6 to 7 pm	14548	6 to 7 pm	14548	3894.58	1947.29	0	5.022339677	6	6	6	6
7 to 8 pm	10930	7 to 8 pm	10930	3894.58	1947.29	0	5.576757097	6	6	6	6
8 to 9 pm	3216	8 to 9 pm	3216	3216	1947.29	0	7.278916613	6	6	6	6
9 to 10 pm	2412	9 to 10 pm	2412	2412	1947.29	0	6.554156452	6	6	6	6
10 to 11 pm	1206	10 to 11 pm	1206	1206	1206	0	6.922576694	6	6	6	6
11 to 12 am	402	11 to 12 am	402	402	402	0	7.126923952	6	6	6	6
12 to 1 am	0	12 to 1 am	0	0	0	0	7.048557419	6	6	6	6
1 to 2 am	0	1 to 2 am	0	0	0	0	6.81089875	6	6	6	6
2 to 3 am	0	2 to 3 am	0	0	0	0	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	0	3 to 4 am	0	0	0	0	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	0	4 to 5 am	0	0	0	0	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	0	5 to 6 am	0	0	0	0	4.67285575	5.55	5.55	5.55	5.55
Average demand	3894.58	Sum of shifted demand	40403.9	55768.4	74902		Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]	136163.5	161804.3	138473.2	107468.5

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2025 for case 2

	2025	2025	BAU	SCN 1	SCN 2	SCN3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	8780	7 to 8 am	8780	5527.42	2763.71	0	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	8780	8 to 9 am	8780	5527.42	2763.71	0	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	8780	9 to 10 am	8780	5527.42	2763.71	0	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	10598	10 to 11 am	10598	19947.7	23664.8	28214.3	3.301330645	6	5.5	5	4.5
11 to 12 noon	3636	11 to 12 noon	3636	12985.7	16702.8	21252.3	3.173446524	6	5.5	5	4.5
12 to 1 pm	2424	12 to 1 pm	2424	11773.7	15490.8	20040.3	2.942637532	6	5.5	5	4.5
1 to 2 pm	1818	1 to 2 pm	1818	11167.7	14884.8	19434.3	2.774496702	6	5.5	5	4.5
2 to 3 pm	3030	2 to 3 pm	3030	12379.7	16096.8	20646.3	2.613476468	6	5.5	5	4.5
3 to 4 pm	5454	3 to 4 pm	5454	14803.7	18520.8	23070.3	3.139715468	6	5.5	5	4.5
4 to 5 pm	13628	4 to 5 pm	13628	5527.42	2763.71	0	4.10220629	6	6	6	6
5 to 6 pm	18476	5 to 6 pm	18476	5527.42	2763.71	0	4.701368629	6	6	6	6
6 to 7 pm	20900	6 to 7 pm	20900	5527.42	2763.71	0	5.022339677	6	6	6	6
7 to 8 pm	15446	7 to 8 pm	15446	5527.42	2763.71	0	5.576757097	6	6	6	6
8 to 9 pm	4848	8 to 9 pm	4848	4848	2763.71	0	7.278916613	6	6	6	6
9 to 10 pm	3636	9 to 10 pm	3636	3636	2763.71	0	6.554156452	6	6	6	6
10 to 11 pm	1818	10 to 11 pm	1818	1818	1818	0	6.922576694	6	6	6	6
11 to 12 am	606	11 to 12 am	606	606	606	0	7.126923952	6	6	6	6
12 to 1 am	0	12 to 1 am	0	0	0	0	7.048557419	6	6	6	6
1 to 2 am	0	1 to 2 am	0	0	0	0	6.81089875	6	6	6	6
2 to 3 am	0	2 to 3 am	0	0	0	0	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	0	3 to 4 am	0	0	0	0	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	0	4 to 5 am	0	0	0	0	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	0	5 to 6 am	0	0	0	0	4.67285575	5.55	5.55	5.55	5.55
Average demand	5527.42	Sum of shifted demand	56098.1	78400.6	105698		Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]	200790.8	255713.6	231644.6	197088.1

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2027 for case 2

	2027	2027 BAU	SCN 1	SCN 2	SCN 3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	21028	7 to 8 am	21028	13936.1	6968.04	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	21028	8 to 9 am	21028	13936.1	6968.04	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	21028	9 to 10 am	21028	13936.1	6968.04	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	25870	10 to 11 am	25870	48938.9	58511.6	2.934516129	6	5.5	5	4.5
11 to 12 noon	9684	11 to 12 noon	9684	32752.9	42325.6	2.820841355	6	5.5	5	4.5
12 to 1 pm	6456	12 to 1 pm	6456	29524.9	39097.6	2.615677806	6	5.5	5	4.5
1 to 2 pm	4842	1 to 2 pm	4842	27910.9	37483.6	2.46621929	6	5.5	5	4.5
2 to 3 pm	8070	2 to 3 pm	8070	31138.9	40711.6	2.323090194	6	5.5	5	4.5
3 to 4 pm	14526	3 to 4 pm	14526	37594.9	47167.6	2.790858194	6	5.5	5	4.5
4 to 5 pm	33940	4 to 5 pm	33940	13936.1	6968.04	4.10220629	6	6	6	6
5 to 6 pm	46852	5 to 6 pm	46852	13936.1	6968.04	4.701368629	6	6	6	6
6 to 7 pm	53308	6 to 7 pm	53308	13936.1	6968.04	5.022339677	6	6	6	6
7 to 8 pm	38782	7 to 8 pm	38782	13936.1	6968.04	5.576757097	6	6	6	6
8 to 9 pm	12912	8 to 9 pm	12912	12912	6968.04	7.278916613	6	6	6	6
9 to 10 pm	9684	9 to 10 pm	9684	9684	6968.04	6.554156452	6	6	6	6
10 to 11 pm	4842	10 to 11 pm	4842	4842	4842	6.922576694	6	6	6	6
11 to 12 am	1614	11 to 12 am	1614	1614	1614	7.126923952	6	6	6	6
12 to 1 am	0	12 to 1 am	0	0	0	7.048557419	6	6	6	6
1 to 2 am	0	1 to 2 am	0	0	0	6.81089875	6	6	6	6
2 to 3 am	0	2 to 3 am	0	0	0	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	0	3 to 4 am	0	0	0	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	0	4 to 5 am	0	0	0	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	0	5 to 6 am	0	0	0	4.67285575	5.55	5.55	5.55	5.55
Average demand	13936.1	Sum of shifted demand	138413	195850	265018	Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]				
							526336.1	709534.8	672301.9	609189.1

Estimation of Average cost to serve, average cost to charge and Average profit to utility for 2030 for case 2

	2030	2030 BAU	SCN 1	SCN 2	SCN 3	Cost to serve	BAU tariff	tariff 1	tariff 2	tariff 3
6 am to 7 am	0	6 am to 7 am	0	0	0	4.980238417	6.45	6.45	6.45	6.45
7 to 8 am	70528	7 to 8 am	70528	56070.2	28035.1	4.77582975	6.45	6.45	6.45	6.45
8 to 9 am	70528	8 to 9 am	70528	56070.2	28035.1	4.361875473	6.45	6.45	6.45	6.45
9 to 10 am	70528	9 to 10 am	70528	56070.2	28035.1	3.774376774	6.45	6.45	6.45	6.45
10 to 11 am	93289	10 to 11 am	93289	180475	220770	2.567701613	6	5.5	5	4.5
11 to 12 noon	45522	11 to 12 noon	45522	132708	173003	2.468236185	6	5.5	5	4.5
12 to 1 pm	30348	12 to 1 pm	30348	117534	157829	2.288718081	6	5.5	5	4.5
1 to 2 pm	22761	1 to 2 pm	22761	109947	150242	2.157941879	6	5.5	5	4.5
2 to 3 pm	37935	2 to 3 pm	37935	125121	165416	2.032703919	6	5.5	5	4.5
3 to 4 pm	68283	3 to 4 pm	68283	155469	195764	2.442000919	6	5.5	5	4.5
4 to 5 pm	131224	4 to 5 pm	131224	56070.2	28035.1	4.10220629	6	6	6	6
5 to 6 pm	191920	5 to 6 pm	191920	56070.2	28035.1	4.701368629	6	6	6	6
6 to 7 pm	222268	6 to 7 pm	222268	56070.2	28035.1	5.022339677	6	6	6	6
7 to 8 pm	153985	7 to 8 pm	153985	56070.2	28035.1	5.576757097	6	6	6	6
8 to 9 pm	60696	8 to 9 pm	60696	56070.2	28035.1	7.278916613	6	6	6	6
9 to 10 pm	45522	9 to 10 pm	45522	45522	28035.1	6.554156452	6	6	6	6
10 to 11 pm	22761	10 to 11 pm	22761	22761	22761	6.922576694	6	6	6	6
11 to 12 am	7587	11 to 12 am	7587	7587	7587	7.126923952	6	6	6	6
12 to 1 am	0	12 to 1 am	0	0	0	7.048557419	6	6	6	6
1 to 2 am	0	1 to 2 am	0	0	0	6.81089875	6	6	6	6
2 to 3 am	0	2 to 3 am	0	0	0	5.863105583	5.55	5.55	5.55	5.55
3 to 4 am	0	3 to 4 am	0	0	0	5.179784333	5.55	5.55	5.55	5.55
4 to 5 am	0	4 to 5 am	0	0	0	4.714516583	5.55	5.55	5.55	5.55
5 to 6 am	0	5 to 6 am	0	0	0	4.67285575	5.55	5.55	5.55	5.55
Average demand	56070.2	Sum of shifted demand	523115	764883	1047547	Average profit to utility = [(EV tariff - Cost to serve) x Charging demand]				
							2176896	3077948	3049926	2904431