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Optimising electric heavy duty truck charging on freight corridors in India

Part of RAP and ICCT's *Benefits of EVs Through Smart Charging* Global Project

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Benefits of EVs through smart charging: A joint project by RAP and ICCT

This paper is part of a global project by the Regulatory Assistance Project (RAP) and the International Council on Clean Transportation (ICCT) studying the economic and environmental benefits of deploying smart electric vehicle (EV) charging in specific geographies. The study identifies those benefits as avoided system costs and avoided emissions, and shows how system costs can be reduced based on four use cases in selected areas within the four largest global EV markets: China, the United States, Europe and India.

The global market for EVs is maturing quickly. In China in 2023, about 80,000 zero-emission trucks (ZETs) were sold in the country, a 23% increase in ZET sales from 2022, taking its contribution to 7% of the total truck sales. Similarly, in the EU, the sales of ZETs in 2023 were 3 times the sales in 2022. In the US, the sales of ZETs were 2.3 times the sales in 2022. National and local policies in several jurisdictions targeting tailpipe emissions of road transport vehicles further contributed to this growth, resulting in an increasing global EV fleet over the past decade — these include the European carbon dioxide (CO_2) standards for light-duty vehicles[1] (LDVs) and the light-duty vehicle greenhouse gas emissions regulations in the United States.[2]

With a continuously growing EV fleet, challenges and opportunities arise with regards to its integration into the power grid. If additional demand from EVs remains unmanaged, this would lead to substantial cost increases for meeting their power and delivery needs, as EVs would likely be charged during existing peak periods, thus exacerbating peak demands. If this transition is not managed carefully, the associated growth in electricity demand will lead to higher costs for consumers, the power system and the environment, and may slow down the transition to a cleaner road transport sector.[3,4]

Smart or managed EV charging can help overcome many of these challenges, and EV charging can be utilised to provide optimum system flexibility. Smart charging is a key tool to reduce the consumption of fossil-powered electricity and to integrate more variable renewables into the grid by charging EVs when there is sufficient renewable energy available. In doing so, smart charging can maximise carbon emissions reductions and reduce the need for costly and unnecessary upgrades of the power grid.[5] While smart charging of EV fleets

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[1] European Commission. (2024, 12 February). *CO_2 emission performance standards for cars and vans*. https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en

[2] U.S. Environmental Protection Agency. (2023, 21 November). *Light-Duty vehicle greenhouse gas regulations and standards.* https://www.epa.gov/regulations-emissions-vehicles-and-engines/light-duty-vehicle-greenhouse-gas-regulations-and

[3] Das, H.S., Rahman, M.M., Li, S., & Tan, C.W. (2020, March). Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. *Renewable and Sustainable Energy Reviews,* 120(109618). https://doi.org/10.1016/j.rser.2019.109618

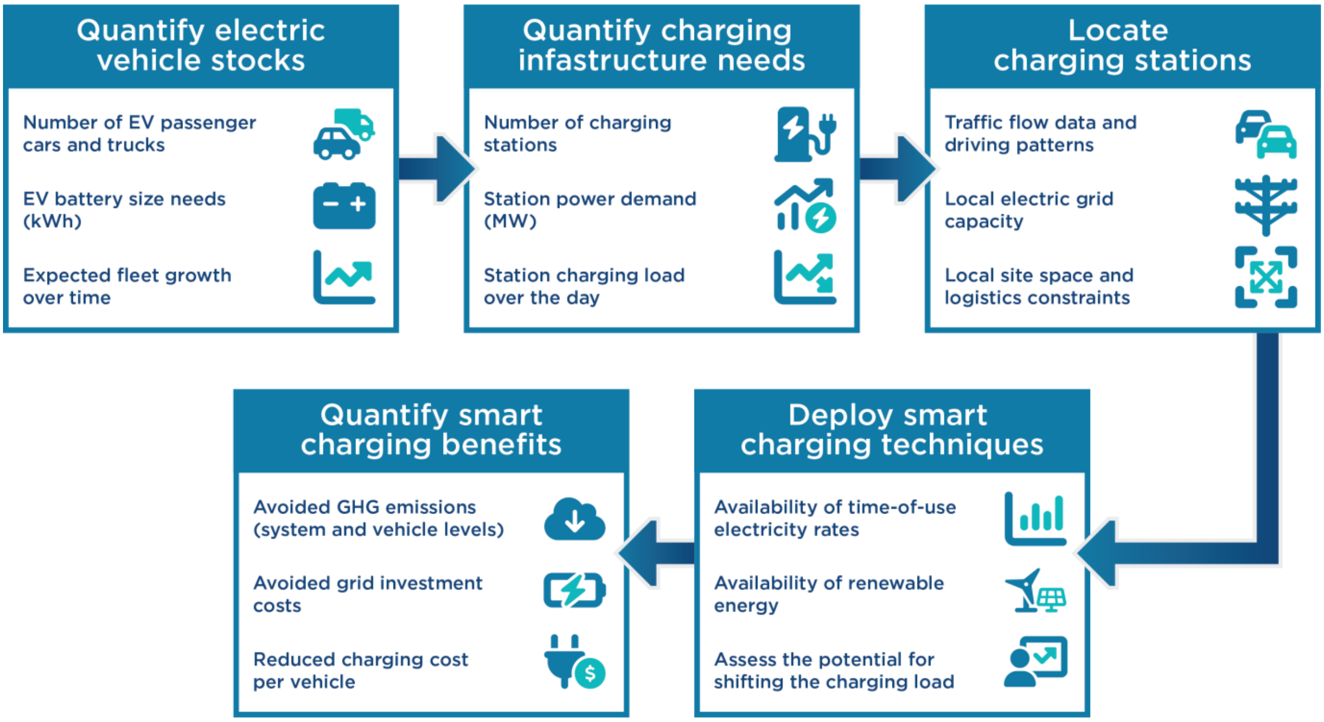
[4] Ashfaq, M., Butt, O., Selvaraj, J., & Rahim, N. (2021, May). Assessment of electric vehicle charging infrastructure and its impact on the electric grid: A review. *International Journal of Green Energy,* 18(7), 657–686. https://doi.org/10.1080/15435075.2021.1875471

[5] Burger, J., Hildermeier, J., Rosenow, J., & Jahn, A. (2022). *The Time is Now. Smart charging of Electric Vehicles in Europe.* Regulatory Assistance Project. https://www.raponline.org/knowledge-center/time-is-now-smart-charging-electric-vehicles/

has been studied from the user benefits point of view,[6] it is important to better understand the value that EVs can have as flexibility assets for the power system[7] and for power networks in large EV markets.[8,9]

The "what-if" analytical framework used in this project to explore the economic and environmental value of smart charging of electric light-duty and heavy-duty vehicles is composed of five sequential steps, summarised in Figure 1.[10]

Figure 1. Framework for smart electric transport



Source: Basma, H. (2024, April 26). *Assessing the Economic and Environmental Benefits of Electric Vehicles Smart Charging*

This interplay between EVs and power systems represents a significant opportunity for demand flexibility, if policymakers and planners in the power and transport sectors integrate smart charging in decision-making, e.g. charging infrastructure build-out. Results of regional case studies illustrate benefits from smart EV charging for both power sector planning and transport policymakers.

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6 Hildermeier, J., Burger, J., Jahn, A., & Rosenow, J. (2023, January). A Review of Tariffs and Services for Smart Charging of Electric Vehicles in Europe. *Energies,* 16(1), 88. https://www.mdpi.com/1996-1073/16/1/88

7 International Energy Agency. (2022, December). *Grid Integration of Electric Vehicles - A manual for policy makers*. https://iea.blob.core.windows.net/assets/21fe1dcb-c7ca-4e32-91d4-928715c9d14b/GridIntegrationofElectricVehicles.pdf

8 Anwar, M.B., Muratori, M., Jadun, P., Hale, E., Bush, B., Denholm, P., Ma, O., & Podkaminer, K. (2022, January). Assessing the value of electric vehicle managed charging: a review of methodologies and results. *Energy & Environmental Science,* 15(2), 466–498. https://doi.org/10.1039/D1EE02206G

9 Xue, L., Jian, L., Ying, W., Xiaoshi, L., & Ying, X. (2020, January). *Quantifying the Grid Impacts from Large Adoption of Electric Vehicles in China*. World Resources Institute. https://www.wri.org/research/quantifying-grid-impacts-large-adoption-electric-vehicles-china

10 Basma, H. (2024, 26 April). *Assessing the Economic and Environmental Benefits of Electric Vehicles Smart Charging* [Unpublished presentation]. EVS37.

Findings, conclusions and recommendations

Background

- The road freight sector in India consumes an estimated 70 million tonnes of oil equivalent (Mtoe), nearly all of which is imported, and emits 213 million tonnes of carbon annually, approximately half of India's transport fuel consumption and transport fuel carbon emissions.
- Electrification of trucks will unlock multiple benefits. It will reduce Indian expenditure on diesel imports — currently over US$30 billion per year for road freight — and enhance energy security. It will reduce carbon emissions: ICCT estimates that replacing diesel with electricity as a fuel would stimulate a 12% reduction in carbon emissions annually by 2030.
- With technology maturity and economies of scale, electrification of freight will allow for a lower total cost of ownership than diesel trucks, and the process of electrification will become self-sustaining. To help make this a reality, the Ministry of Power has proposed 12 national corridors to be converted into e-highways, including the Delhi-Jaipur corridor.
- We conducted a "what-if" analysis of potential social benefits unlocked by smart — rather than non-smart — truck charging along the proposed e-truck Jaipur-Delhi freight corridor until 2030, focusing on 'heavy duty' freight (medium and heavy goods vehicles).
- Smart charging of e-trucks means optimised charging when the cost of electricity is lowest, without compromising users' needs. Smart charging seeks to accommodate in the most efficient way the bottlenecks on the grid, and the growing penetration of cheap but variable renewables.
- Where network constraints are not expected to be an issue, as suggested by the analysis for the Delhi-Jaipur corridor, 'smart charging' may mean 'solar charging': making use of cheap and potentially abundant solar energy.

Main findings

- The value of the flexibility unlocked by smart charging of e-trucks will depend on multiple factors including the extent of grid bottlenecks, renewable curtailment, the costs of motivating new smart behaviours by consumers, the extent of other forms of flexibility in the system such as storage capability, the size of the e-truck fleet, and more. The extent of uncertainty regarding each of these factors means there is significant range in the potential benefits accruing from smart charging.
- This "what-if" analysis suggests that system cost savings unlocked by smart — rather than non-smart — truck charging along the Jaipur-Delhi freight corridor could be significant.
    - Electricity system benefits of smart charging could offer annual savings that reach 300 million Indian rupees (INR) to INR 700 million (roughly US$3.6 million to US$8.4 million) by 2030.

- If, as envisaged by the Indian government, India accommodates a dozen such corridors, savings could be in the range of INR 3.5 billion to 8.5 billion (approximately US$45 million to US$100 million), if similar potential savings from one corridor are extrapolated across multiple corridors.
- Scaling up estimates across a dozen such corridors, this could help reduce carbon emissions by as much as 1 million to 3.5 million tonnes.

Policy recommendations to help meet decarbonisation targets

- Policymakers can accelerate freight electrification by strategically planning and delivering the enabling infrastructure to unlock flexibility offered by smart charging, including by ensuring that the objective of integrating EVs (including trucks) at lowest cost, through EV-based demand response and smart charging, is enshrined in policies and regulations.
- Policymakers could consider introducing tariff designs that reflect cost in a granular and marginal way — both in time and location — and that encompass all costs, including wholesale, network and relevant environmental costs such as carbon.
    - In the short run, scalars or rebates for example could be used to enable lower tariffs during hours of solar production (subject to limits of cost recovery). In this regard the recent solar scalar proposals of the Indian Bureau of Energy Efficiency and Ministry of Power introducing these for certain customer categories are most welcome.[11] In time, solar tariffs may be helpfully accompanied by multi-part network tariffs reflecting each user´s contribution to the costs of meeting network peak.
    - In the longer term this implies a goal of introducing market-based price incentives, i.e., allowing real-time wholesale prices to underpin the development of smart tariffs to EV consumers, with a robust carbon price, and capturing the cost of network constraints in locationally formed prices.[12]

[11] Draft Revised Guidelines and Standards for Electric Vehicle Charging Infrastructure. (2024). BEE. https://beeindia.gov.in/en/draft-revised-guidelines-standards-for-electric-vehicle-charging-infrastructure-for-stake-holders
Gazette of India, Notification No. G.S.R. 437 (E), REGD. No. D. L.-33004/99, CG-DL-E-15062023-246571 (June 14, 2023). Available at https://powermin.gov.in/sites/default/files/webform/notices/30_d_Electricity_Rights_of_Consumers_Amendment_Rules_2023..pdf (last accessed November 2024).

[12] More information: Smart Network pricing. RAP Power System Blueprint. https://www.raponline.org/toolkit/power-system-blueprint/

Introduction

This joint paper by the Regulatory Assistance Project (RAP) and the International Council on Clean Transportation (ICCT) explores the potential benefits of smart charging of freight vehicles in India. The paper is aimed at energy and transport decision-makers and stakeholders in India at the national and regional level.

The investigation drew on ICCT projections of growth in medium and heavy-duty freight fleet electrification, and possibilities for smart charging the e-truck fleet to utilise cheap variable renewable electricity relative to a business-as-usual 'non-smart' charging future scenario. For the purposes of this report, we commissioned the expertise of MP Ensystems Advisory Pvt. Ltd. to explore the potential for flexibility from electric trucks to be used to lower the costs of freight electrification along the key corridor Delhi-Jaipur. We are grateful to MP EnSystems for offering insights to this report. [13]

This inquiry focuses on heavy-duty freight vehicles (trucks, medium goods and heavy goods vehicles, MGV and HGV, which for simplicity we call 'heavy duty vehicles' or HDV) as opposed to light-duty passenger vehicles (typically two, three, and four-wheelers) as there is already a sizeable body of research emerging in India on the impact of passenger vehicle electrification. In comparison, the potential benefits of smart charging in India's current and future electric freight fleets are relatively understudied. Adding to the need to gain deeper insights in this segment is the scale of carbon emissions attributable to freight, and the potential for electrification of trucking to lessen the carbon impact of the sector.

Beneficial electrification of transport means using EVs as flexibility resources to reduce the cost of electrification for users, power grids and the environment.[14] In this process, smart EV charging is key as it can delay or avoid the need for grid upgrades in constrained grids. It can help optimise deployment of energy resources, including avoiding curtailment of cheap renewables, and thereby reduce carbon emissions and support further investment in renewable energy sources (RES). In this paper, 'smart' means optimised charging when the cost of electricity is lowest, without compromising users' needs. It accommodates in the most efficient way limitations and bottlenecks on the grid, and the mix of electricity-generating technologies including the growing penetration of cheap but variable renewables. The focus of the paper is on optimising truck charging along highways by moving a portion of charging into solar hours (taken as 10am to 4pm) to utilise cheap solar PV energy. Smart consumption patterns may be incentivised by accurate price signals that are granular in time and by location, and that reflect all costs including wholesale, network and environmental costs (e.g. the social costs arising from carbon emissions). Smartness is enabled by supportive energy

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[13] The technical analysis by MP Ensystems Advisory Pvt. Ltd. underpinning this report can be found here https://www.mpensystems.com/smart-charging-in-india-study-on-ev-freight-corridor-and-grid-final-versionpdf

[14] "For electrification to be considered beneficial, it must meet one or more of the following conditions without adversely affecting the other two: 1. Saves consumers money over the long run; 2. Enables better grid management; and 3. Reduces negative environmental impacts." Farnsworth D., Kadoch, C., Shipley, J., Lazar, J, & Seidman, N. (2018, June). *Beneficial electrification.* Regulatory Assistance Project. https://www.raponline.org/toolkit/beneficial-electrification/

market structures[15] and rigorous competition. Underpinning all of this is a clear vision for the roll-out of e-trucks, the effective allocation of roles and responsibilities, and strategic planning to guide investment in charging infrastructure.

This paper first presents the Indian policy and market context. It outlines factors that influence the extent of the benefits that may be unlocked by smart charging, and the methodological approach taken to analysing this. It outlines insights from the analysis of scenarios and presents estimates of potential generation cost savings unlocked through the shifting of demand patterns. Finally, the paper presents conclusions, policy recommendations and areas for further research.

Indian market and policy context

India is the world's third largest automobile market, having overtaken Japan in total vehicle sales in 2022 and 2023.[16] In 2021, electric vehicle (EV) sales comprised just 1% of India's vehicle sales across all segments.[17] However, strong year-on-year growth sees India poised to become an increasingly dominant EV market. India's EV sales grew from 0.4% to 1.5% in one year between 2021 and 2022, approximately three times the global average,[18] and by 2023-2024 EVs accounted for 7% of total automobile sales across all vehicle segments.[19] This growth is expected to accelerate rapidly, with one projection suggesting that by 2030 EV sales could comprise more than 40% of India's automotive market and generate over US$100 billion in revenue.[20]

There are currently roughly 4 million freight trucks on the road in India. It is estimated that between 2022 and 2050 this number will quadruple to 17 million.[21] With this, awareness is growing of the potential for electrification to unlock multiple benefits — these are outlined below.

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15 See RAP's blueprint for a clean electricity system (focus on Europe) https://blueprint.raponline.org/ including focus on locational marginal pricing https://blueprint.raponline.org/locational-marginal-pricing/

16 Hanada, R. (2024, 13 January). *India tops Japan again as world's no. 3 auto market. Nikkei Asia*. https://asia.nikkei.com/Business/Automobiles/India-tops-Japan-again-as-world-s-No.-3-auto-market (last accessed February 2024).

17 The International Council on Clean Transportation (ICCT). (2024). *Electric vehicle demand incentives in India.* https://theicct.org/wp-content/uploads/2024/06/ID-169-FAME-opps_report_final.pdf (last accessed August 2024).

18 Jaeger, J. (2023, 14 September). *These countries are adopting electric vehicles the fastest*. World Resources Institute. https://www.wri.org/insights/countries-adopting-electric-vehicles-fastest (last accessed February 2024).

19 The International Council on Clean Transportation (ICCT). (2024, July). *Electric vehicle demand incentives in India.* https://theicct.org/wp-content/uploads/2024/06/ID-169-FAME-opps_report_final.pdf (last accessed August 2024).

20 Seetharaman, M., et al. (2023, 7 December). *India Electric Vehicle Report 2023.* https://www.bain.com/insights/india-electric-vehicle-report-2023/ (last accessed February 2024).

21 Aayog, N. (2022, September). *Transforming Trucking in India: Pathways to Zero Emission Truck Deployment.* Rocky Mountain Institute (RMI). https://www.niti.gov.in/sites/default/files/2023-02/ZETReport09092022.pdf (last accessed February 2024).

Electrification of trucking reduces India's oil import bill and enhances security

The road freight sector in India consumes an estimated 70 million tonnes of oil equivalent (Mtoe). Over 82% of India's crude oil is imported, and road freight accounts for a quarter of India's annual import expenditures on oil products (primarily diesel and gasoline), which currently stand at US$119.2 billion.[22] Electrification of trucks may therefore support energy security by reducing dependence on foreign fossil fuels and unlock the benefits that come with substituting expensive fuel imports with cheap locally generated electricity.

Electrification of trucking supports India's decarbonisation efforts

The road freight sector in India emits 213 million tonnes of carbon annually.[23] This accounts for approximately half of the country's transport fuel carbon emissions.[24] India's 4.6 million trucks alone account for 44% of the transport sector's CO_2 emissions. India has seen year-on-year growth in EV sales, with substantial emissions reductions and air quality improvements. Electrification will support decarbonisation, particularly as the carbon intensity of the electricity mix diminishes over time.

To reach the Indian government's net-zero target by 2070, 100% battery electric truck (BET) sales are needed by 2050;[25] and to comply with India's commitment to limit global warming below 2°C, 100% of new sales would need to be e-trucks five years earlier, by 2045.[26] Electrification may be particularly important for HDVs, which, owing to their size, contribute as much as 83% of all carbon emissions from India's freight transport sector, and which therefore have the potential for the most substantial emissions abatement.[27]

Electrification of trucking reduces deaths from poor air quality, among other benefits

BETs could bring multiple benefits including reduced conventional air pollution along India's highways and in congested areas.[28] India ranks second globally in premature deaths from

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22 Natural Resources Defense Council (NRDC), Administrative Staff College of India (ASCI). (2023, November). *Energizing Freight: Policy Toolkit for Medium and Heavy Duty Truck Electrification in India*. https://www.nrdcindia.org/pdf/NRDC_%20Heavy_Trucking.pdf (last accessed February 2024).

23 Ravuri, S. and Aswathi, K.P. (2022). *The Potential to Electrify Freight Transportation in India.* Center for Science, Technology, and Policy (CSTEP). https://cstep.in/drupal/sites/default/files/2022-06/The%20Potential%20to%20Electrify%20Freight%20Transportation%20in%20India_Final_03.06.22.pdf (last accessed February 2024).

24 Ravuri, S. and Aswathi, K.P, (2022).

25 Singh, N. & Yadav, A. (2024). *Assessing the scale of zero-emission truck deployment required for meeting India's net-zero goal.* ICCT. https://theicct.org/wp-content/uploads/2024/04/ID-58-%E2%80%93-India-ZET_final.pdf

26 Sen, A. & Miller, J. (2023, September). *Vision 2050: Update on the global zero-emission vehicle transition in 2023.* ICCT. https://theicct.org/publication/vision-2050-global-zev-update-sept23/

27 Ravuri, S. and Aswathi, K.P, (2022).

28 Abhyankar, N., et al. (2022, October). *Freight Trucks in India are Primed for Electrification*. Berkeley Lab - Ernesto Orlando Lawrence Berkeley National Laboratory (LBNL). https://eta-publications.lbl.gov/sites/default/files/electric_trucks_in_india_-_final_nov7.pdf (last accessed February 2024).

transportation-related emissions, with an estimated 74,000 deaths in 2015, an increase of 28% from 2010.[29] Delhi has the highest transportation-emissions mortality rate at 9 deaths per 100,000 population. [30] On-road diesel vehicles contributed as much as 60% of the transportation health burden in Delhi.[31] Other benefits include potential reduced exposure to fuel price volatility, which is a challenge for diesel-run trucks.

The time is right to plan 'smart' into the e-trucks transition

Electrification of freight transport is receiving increasing attention within India.[32] Studies suggest that BETs could have a lower total cost of ownership than diesel trucks.[33] The need for supportive EV charging infrastructure has been identified,[34] including a massive projected growth in charging stations, up from a low baseline level of 1.8 million charging points in 2021.[35]

The Government of India has introduced enabling regulations that would allow for a discounted electricity tariff during solar hours, creating incentives for higher EV charging during periods when there is more solar power in the system. Specifically, via the Ministry of Power's notification,[36] commercial and industrial (C&I) customers above a certain consumption threshold (10 kW) and who have smart meters installed are to receive at least a 20% discount, during solar hours, compared to the normal tariff (effective from April 2024).[37] Other customers such as those in the residential category, with smart meters, are eligible for the discounted solar tariff of at least 20% less than the normal tariff during solar hours (between 09:00 am and 04:00 pm) from April 2025.[38] During peak hours, C&I customers will be charged not less than 1.20 times the normal tariff, while residential and other customers

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29 Abhyankar, N., et al. (2022, October). *Freight Trucks in India are Primed for Electrification*. Berkeley Lab - Ernesto Orlando Lawrence Berkeley National Laboratory (LBNL). https://eta-publications.lbl.gov/sites/default/files/electric_trucks_in_india_-_final_nov7.pdf (last accessed February 2024).

30 The International Council on Clean Transportation (ICCT). (2019, June). *Health impacts of air pollution from transportation sources in Delhi*. https://theicct.org/wp-content/uploads/2022/01/ICCT_factsheet_health_impact_airpollution_Delhi_20190705.pdf (accessed August 2024).

31 The International Council on Clean Transportation (ICCT). (2019, June).

32 Climate Group. (2022, October). *Early Market Outlook Report – Electrification of Medium and Heavy Duty Trucks in India*. https://www.theclimategroup.org/our-work/publications/early-market-outlook-report-electrification-medium-and-heavy-duty-trucks (last accessed February 2024).

33 This finding is based on maturity of the technology. Achieving maturity in turn requires operations to have unlocked benefits of economies of scale and accumulation of experience. The authors consider this requires sustained public support over a long period of infancy. Abhyankar, N., et al. (2022, October).

34 Ernst & Young (EY), Indian Venture and Alternate Capital Association (IVCA), IndusLaw. (2022). *Electrifying Indian Mobility.* https://assets.ey.com/content/dam/ey-sites/ey-com/en_in/topics/automotive-and-transportation/2022/ey-electrifying-indian-mobility-report.pdf

35 KPMG. (2022, August). *Carpe Diem! Electric Vehicle Charging – The Next Big Opportunity*. https://assets.kpmg.com/content/dam/kpmg/in/pdf/2022/08/electric-vehicle-charging-next-big-opportunity-infrastructure.pdf (last accessed February 2024).

36 Gazette of India, Notification No. G.S.R. 437 (E), REGD. No. D. L.-33004/99, CG-DL-E-15062023-246571 (June 14, 2023).

37 Ministry of Power, Government of India, Press Information Bureau, *Implementation of Time of Day Electricity Tariff System* (2023). Available at https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1945236 (last accessed November 2024).

38 Ministry of Power, Government of India, Press Information Bureau. (2023).

will be charged not less than 1.10 times the normal tariff.[39] This differential tariff structure sends a price signal to consumers to use electricity — including for EV charging — when they receive a rebate, i.e., cheaper power.

Over and above this, the Ministry of Power has explicitly directed that all EV charging stations should benefit from a dedicated "EV Charging Tariff." According to guidelines issued in 2024,[40] which formally define "Smart Charging" in the Indian context,[41] the EV Charging Tariff should be 0.7 times the Average Cost of Supply (ACoS) during the solar hours of 09:00 am to 04:00 pm (i.e., a discount), and should be 1.3 times the ACoS during the remainder of the day (non-solar hours). Furthermore, through a subsequent memorandum, the Ministry affirmatively extended the application of the guidelines — including the provisions on discounted solar tariffs — to EV battery charging stations and battery swapping stations.[42]

The transition will incur up-front costs to invest in necessary infrastructure, and the new system that materialises will incur running costs. The time is right therefore to plan and to ensure the transition is smart. This means not investing more than is needed and making use of the cheapest resources to unlock these benefits at least cost. A key element of this will be a coherent strategy to unlock flexibility in e-truck demand patterns, to save on grid costs, and to utilise new cheap and clean renewable resources.

This paper contributes to the growing body of knowledge on this issue[43] — including policy papers on other regions in this RAP-ICCT series — with an overview of the MP Ensystems analysis of the potential value of smart price signals and charging patterns, and presentation of key recommendations. These fit well with draft government guidelines proposing differential tariffs for EV charging stations to incentivise charging during solar hours,[44] underlining the timeliness of this scenario analysis.

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[39] Ministry of Power, Government of India, Press Information Bureau. (2023).

[40] Ministry of Power, Government of India, No. 12/2/2018-EV (Comp No. 241852), *Guidelines for Installation and Operation of Electric Vehicle Charging Infrastructure-2024* (September 17, 2024). Available at https://beeindia.gov.in/sites/default/files/Guidelines%20and%20Standards%20for%20EVCI%20dated%2017-09-2024_compressed.pdf (last accessed November 2024).

[41] "Smart Charging is a way to optimize the charging process according to distribution grid constraints, utilization of renewable energy sources and customer preference. This helps reducing transformer overloading requirement for enhancing capability of grid, mitigating voltage fluctuation in grids having high penetration of renewable energy sources. Smart charging includes bi-directional vehicle to grid integration." See Ministry of Power, Government of India, No. 12/2/2018-EV (Comp No. 241852).

[42] Bureau of Energy Efficiency (BEE), F.No. 49/02/BEE-EV-MoP/2024/2973, *Request for Comments on Draft Guidelines for Installation and Operation of Battery Swapping and Battery Charging Stations* (October 7, 2024). Available at https://beeindia.gov.in/sites/default/files/2024-10/Draft%20Guidelines%20for%20Installation%20and%20Operation%20of%20Battery%20Swapping%20%20Battery%20Charging%20Stations_0.pdf (last accessed November 2024).

[43] See: Aayog, N. (2021). *Integration Of Electric Vehicles Charging Infrastructure with Distribution Grid: Global Review, India's Gap Analyses and Way Forward*; Aayog, N., Rocky Mountain Institute (RMI). (2022, September). *Transforming Trucking in India: Pathways to Zero Emission Truck Deployment*. https://www.niti.gov.in/sites/default/files/2023-02/ZETReport09092022.pdf

[44] Knowledge & News Network (2024, 2 July). *Power Ministry releases draft guidelines for EV charging infrastructure.* https://knnindia.co.in/news/newsdetails/sectors/power-ministry-releases-draft-guidelines-for-ev-charging-infrastructure

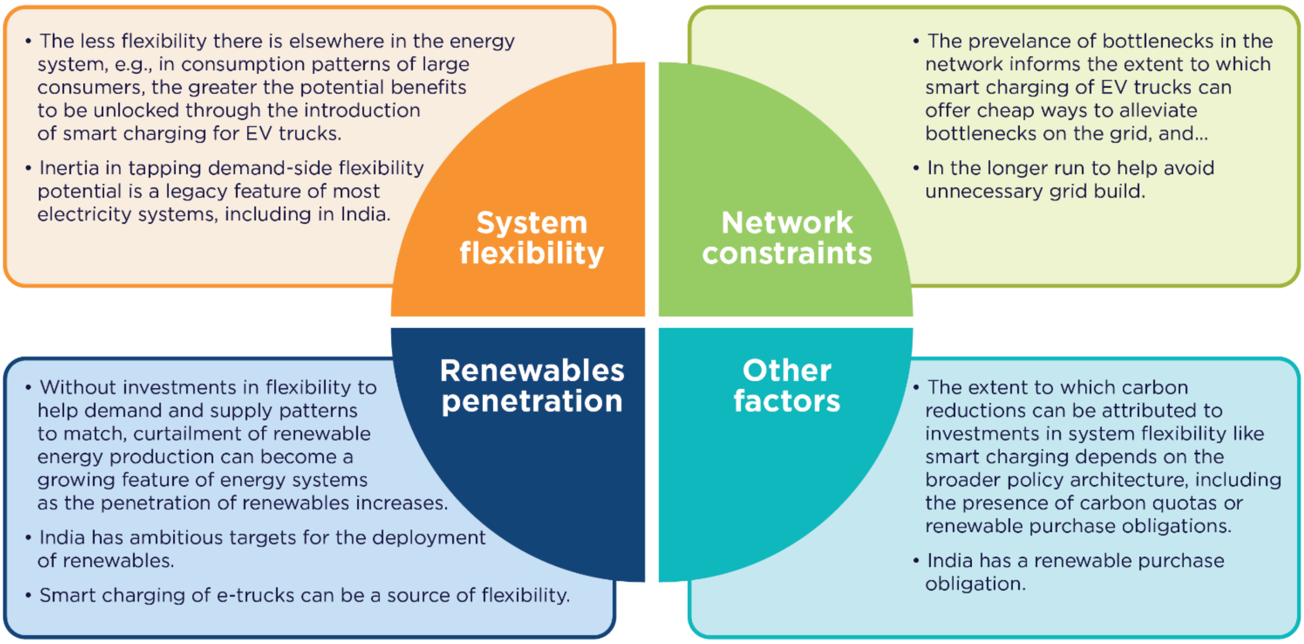
Analysis

This section provides an overview of the potential benefits that may be unlocked by the use of smart rather than non-smart charging. It then outlines the analytical methods employed to assess the potential value of smart e-truck charging.

Multiple factors influence the value of smart charging for e-trucks

E-truck charging is not just a source of new demand for electricity, it is also a potential source of flexibility — a resource that can be implemented to make best use of the production of electricity from variable renewables and of the limited capacity on the wires of the network. Thus, the value of smart e-truck charging depends on the extent to which other forms of flexibility have already unlocked this value, the extent to which bottlenecks in the system are proving costly, the extent to which renewable energy is growing[45] (and potentially wasted through poor alignment of demand and supply), and interactions with the broader policy framework[46], as outlined in Figure 2.

Figure 2. Factors that influence the system value of going smart in e-truck charging



The analysis of the potential impact of smart charging builds on the development of business-as-usual demand patterns of e-truck charging prepared by ICCT (in turn with some input from

[45] In April 2023, the government of India issued notification of bids for 50 GW of renewable energy capacity annually for the next five years, to achieve the target of 500 GW by 2030. India – Country Commercial Guide. (2024, 12 January). *Renewable Energy*. U.S. International Trade Administration. https://www.trade.gov/country-commercial-guides/india-renewable-energy#:~:text=India%20plans%20to%20double%20its,of%20500%20GW%20by%202030.

[46] 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.

MP Ensystems to develop the shape of demand within 24-hour periods, outlined below). The technical annex outlines the work of ICCT to derive business-as-usual (non-smart) energy consumption patterns of e-trucks.

Assessment of utility profitability and the value of smartness

The scenario analysis, which focused on the period 2023-2030, explored the confluence of supply and demand under different scenarios of charging 'smartness' to estimate changes in the 'profitability of the utility'. This parameter is derived from the interplay of 'average cost of supply' (generation cost) and 'average consumer cost' (tariffs) for the utility. When multiplied by energy sales, this gives total daily profit of the utility. Given the broadly flat tariffs, the change in profit can act as a proxy for social cost saving potential (assuming the rebate just covers the consumer's costs associated with flexing their demand patterns) and is therefore a key parameter of interest.

We now outline each of the main elements of the model as they link to supply, the grid and demand, pointing out the many simplifying assumptions employed. These were designed and tested to offer useful simplifications of reality, but they nevertheless have limitations and caveats which are touched on in the further research section.

Supply

The model uses Indian Energy Exchange (IEX)[47] market rates for power generation costs at different times of day to approximate the average cost to serve energy in 2023.[48] Coal is an important determinant of this cost, given that it accounts for around 70% of electricity generation.[49] Significant growth of renewable energy, particularly solar, is envisaged over the period to 2030; this is reflected in projections of diminishing cost to serve to 2030 (Figure 3).[50] The model builds on the possibility that significant growth in variable renewables penetration,

47 For more detail, see the IEX Market Snapshot. https://www.iexindia.com/market-data/day-ahead-market/market-snapshot?interval=ONE_FOURTH_HOUR&dp=SELECT_RANGE&showGraph=true&toDate=30-04-2023&fromDate=01-04-2023

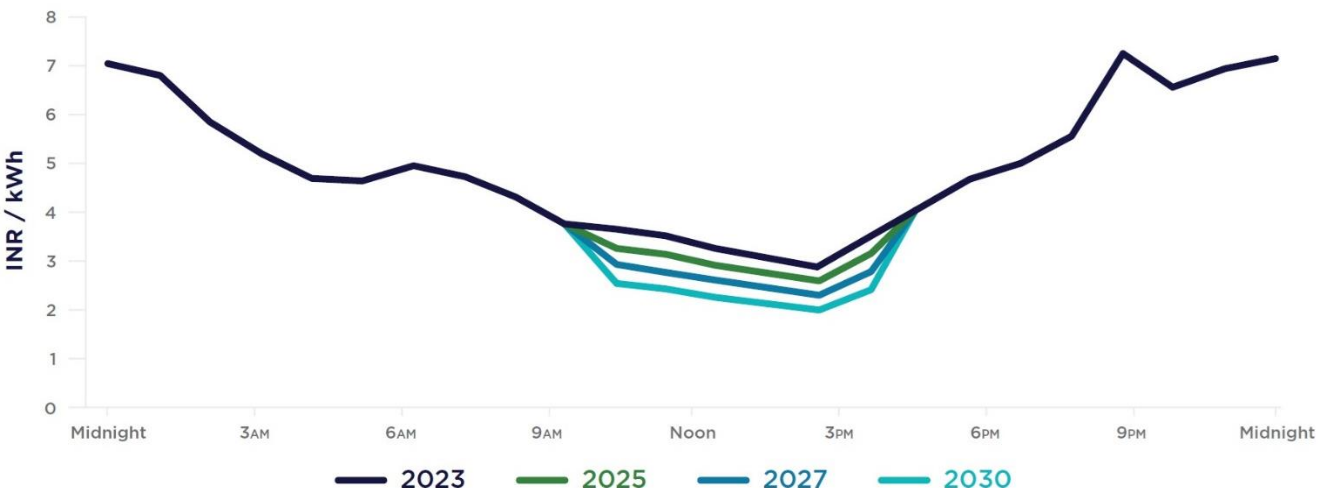
48 Average costs rather than marginal were used owing to data availability considerations. IEX prices for the average of April-May 2023 underpins the 2023 cost data.

49 IEA. (n.d.). *Electricity*. https://www.iea.org/countries/india/electricity

50 Simulated cost reductions in solar hours over 2023-2030 build on the rationale that growing solar pv penetrations over time allow for average costs during solar hours to fall gradually towards levelised costs of solar pv. Solar pv auctions have reached clearing prices as low as 2 INR/KWh (https://www.pv-magazine-india.com/2020/11/26/india-draws-new-record-low-solar-tariff-of-inr-2-kwh/), and there is an expectation that solar pv levelised costs will continue to fall over time. Given uncertainties of exact cost reductions, MP Ensystems apply a 10% reduction in average (real) cost to serve during solar hours in 2025, 20% in 2027 and 30% in 2030, such that costs gradually fall to a minimum of around 2 INR/KWh by 2030. As for non-solar hours, estimates of 2025, 2027 and 2030 costs are unchanged from 2023 costs, reflecting a hypothesis that costs change only according to broad inflation and thus can be thought of as being expressed in 2023 prices. All prices, costs and values may be considered as approximating real 2023 prices.
MP Ensystems Advisory Pvt. Ltd. (2024). *Smart charging in India.* https://www.mpensystems.com/smart-charging-in-india-study-on-ev-freight-corridor-and-grid-final-versionpdf

specifically solar PV, could be absorbed by e-trucks, the prospect of which could spur further investment in this electricity generation technology.[51]

Figure 3. Average cost to serve



Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

Grid

Drawing on stakeholder consultation, MP Ensystems elected to focus the scenario analysis on the potential value of smart e-truck charging in optimising wholesale generation costs, rather than on managing constraints in the grid. The key justification for this is that massive grid build-out is already built into plans[52] — plus interviews were carried out which suggested that new demand from the electrification of trucks is not expected to reach the limits of the grid in the near future.[53] It was therefore concluded that it would be more useful for the scenario analysis to explore the role of smartness in optimising generation costs. This assumption may merit revisiting and further research (see limitations) as truck charging infrastructure grows.

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51 We discuss later the extent to which new build of solar PV could be attributed to smart (versus non-smart) charging of e-trucks in the presence of broader policy measures, notably India’s renewable portfolio obligation.

52 Central Electricity Authority (CEA). (2024). *Draft Distribution Perspective Plan 2030.* https://cea.nic.in/wp-content/uploads/notification/2024/02/Public_Notice__for_comments___DIstribution_Pers_Plan_2030-1.pdf (Refer Annexure 2)
Government of National Capital Territory of Delhi Power Department. (n.d.). *Vision Document of Power Department for Master Plan -2041.* https://power.delhi.gov.in/sites/default/files/power/circulars-orders/vision_doc_mpd-2041.pdf
CEA. (2023). *Electricity distribution network planning criteria*. https://cea.nic.in/wp-content/uploads/notification/2024/01/Final_Approved__Revised_Distribution_Planning_Criteria.pdf

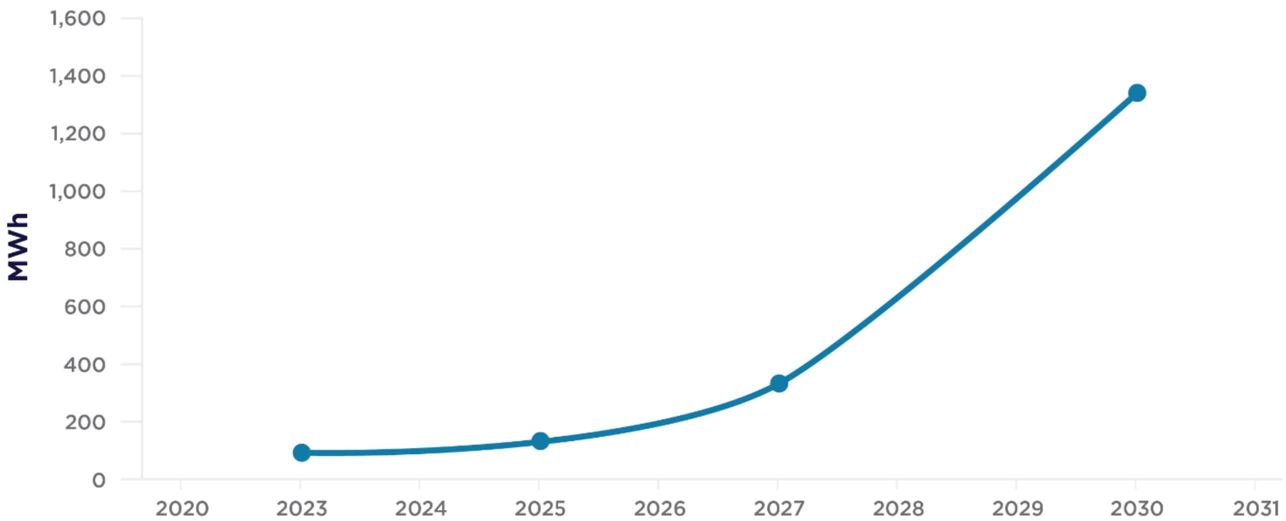
53 MP Ensystems’ interactions with DISCOMs suggested that grid network issues due to the connection of bulk loads are not expected to lead to congestion or grid stability issues, and that EV charging to date has a relatively minor impact on the grid.

Demand

Non-smart charging — business as usual

The scenario analysis draws on ICCT's most ambitious ('all out')[54] projections of demand growth for HDV electrification along the Delhi-Jaipur road corridor from 2023-2030 (see Figure 4).[55]

Figure 4. Simulated annual demand from electrification of trucks along the Delhi-Jaipur corridor



Data source: ICCT. (2024). [Unpublished raw data projecting demand growth of heavy duty vehicle electrification from 2023-2030. See annex for description of methods.]

Baseline business-as-usual daily (24-hour) load curves were simulated for the business-as-usual non-smart charging scenario for each year examined — 2023, 2025, 2027, 2030 — to allow comparison of smart charging scenarios against a counterfactual.

Depot charging was assumed to happen exclusively at night (from 10pm to 6am), a pattern that resembles most depot charging in other global regions studied.[56] The same daily load shape is applied for each of the years examined, but accounting for the expected growth of electricity demand. Figure 5[57] shows the expected load shape during the day in 2030 for business as usual.

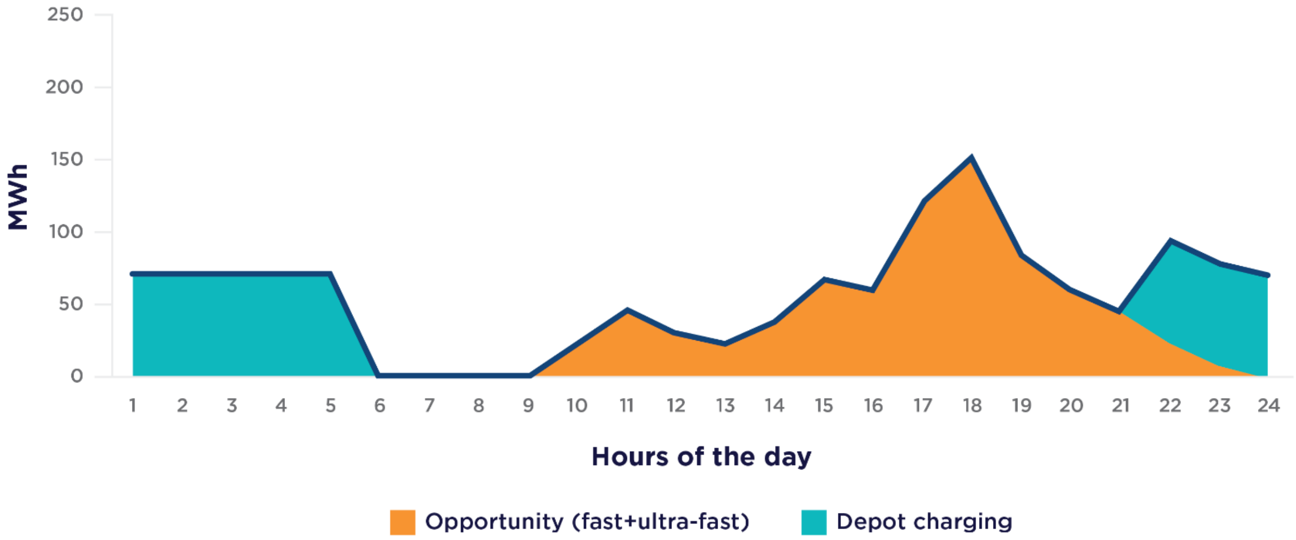
[54] This scenario follows the ICCT's Vision 2050 projections, where India will comply with the sub-2°C warming goal by 2050 under the Paris Agreement. In this scenario, trucks will be 100% electric by 2045, and the pace of electrification is faster.

[55] ICCT. (2024). [Unpublished raw data projecting demand growth of heavy duty vehicle electrification from 2023-2030]

[56] RAP-ICCT. (2020). *Electrifying EU city logistics: An analysis of energy demand and charging cost.* https://www.raponline.org/knowledge-center/electrifying-eu-city-logistics-analysis-energy-demand-charging-cost/

[57] MP Ensystems Advisory Pvt. Ltd., 2024.

Figure 5. Charging demand business as usual 2030 (depot charging occurs overnight)



Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

Smart charging scenarios

The scenario analysis unlocks flexibility by offering consumers rebates on tariffs that effectively lower the cost of charging during the main daytime hours of solar production. The three scenarios of demand-side flexing are outlined in Table 1. Note that the analysis assumes that other potential sources of demand-side flexibility (for instance industrial demand) are unrealised, and therefore do not compete to absorb the potential value that could be unlocked in shifting demand to utilise cheap solar energy. Note also that these scenarios do not include behavioural constraints on e-truck fleets such as traffic restrictions or patterns.

Table 1. Demand shift potential (at depots and public chargers) and accompanying rebates by scenario

Scenario	Demand-shift potential	Rebate
1	Demand exceeding 24-hour average demand is assumed to be shifted into solar hours.	The assumed cost to the utility of unlocking this flexibility is a rebate to the consumer of 0.5 INR/kWh, representing a reduction of about 10% on the price of energy.
2	Demand exceeding half of the 24-hour average demand is assumed to be shifted into solar hours. This allows more demand shift potential than Scenario 1.	The assumed cost to the utility of unlocking this flexibility is a rebate to the consumer of 1 INR/kWh, representing a reduction of about 20% on the price of energy.
3	All demand during non-solar hours is assumed to be shifted into solar hours. This scenario assumes the greatest flexibility potential, such that EV heavy truck charging is zero during non-solar PV hours, having all been shifted to solar hours.	The assumed cost to the utility of unlocking this flexibility is a rebate to the consumer of 1.5 INR/kWh, representing a reduction of about 30% on the price of energy.

The rebates presented in Table 1 offer three possible scenarios of the enticement assumed necessary to unlock flexibility. The rebates are built around the Government´s proposed 20% tariff reduction during solar hours[58] — a rebate of 20% forms the central scenario (scenario 2) — while scenarios 1 and 3 explore sensitivities around this (rebates of 10% and 30%). These rebates reduce the costs for consumers during solar PV daytime hours, compared to the non-smart business-as-usual scenario. These are input assumptions rather than a subject of inquiry.

The absolute and proportionate volumes of energy assumed shifted are presented in Table 2.[59]

Table 2. EV charging demand shifted into solar hours (kWh/day)

	Scenario 1	Scenario 2	Scenario 3
2023 kWh/day	29,726	54,148	81,410
2025 kWh/day	40,344	75,786	114,478
2027 kWh/day	97,241	188,493	286,046
2030 kWh/day	343,640	725,584	1,118,075
% of daily demand (unchanged over years)	**32%**	**58%**	**87%**

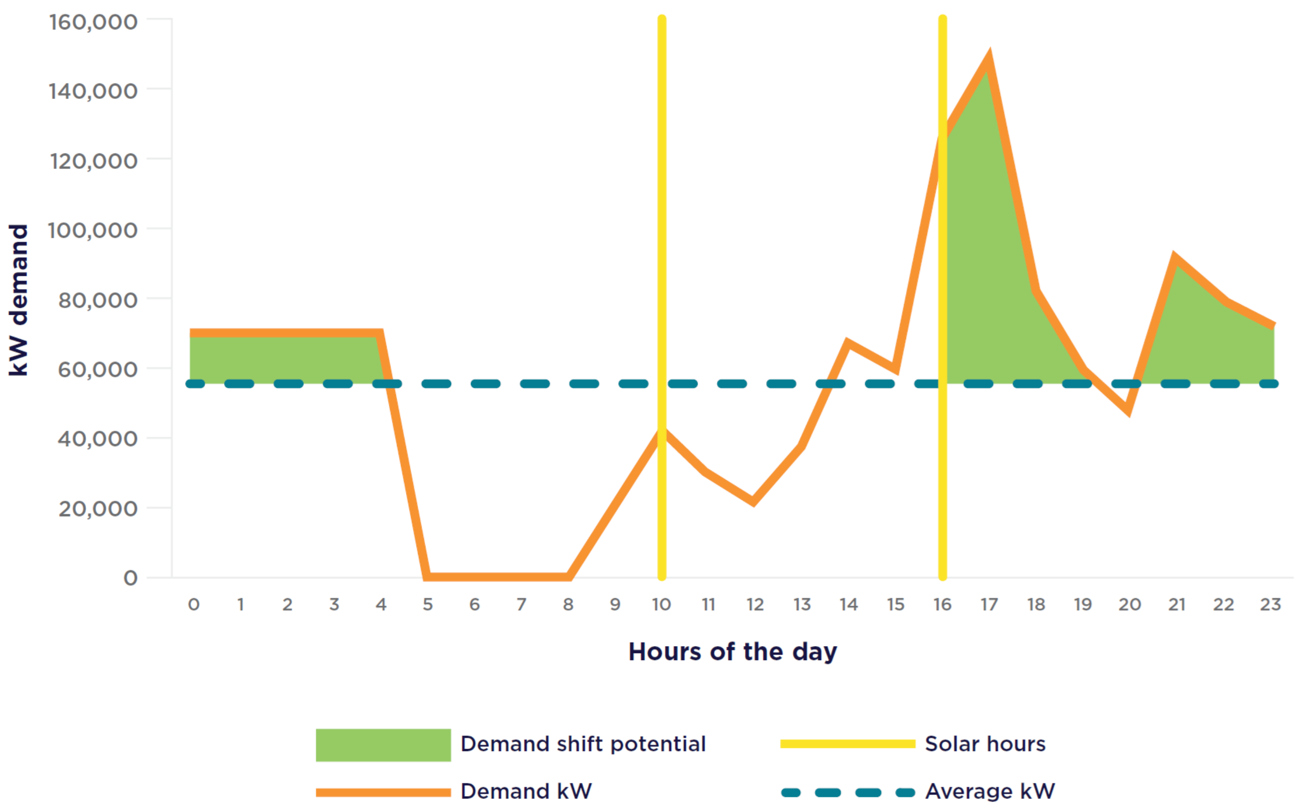
Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

58 Ministry of Power, Government of India, No. 12/2/2018-EV (Comp No. 241852). (September 17, 2024).

59 MP Ensystems Advisory Pvt. Ltd., 2024.

Figure 7[60] provides an illustration of the potential demand in 2030 that Scenario 1 assumes can be shifted into solar hours (10am-4pm) through a smart charging rebate.

Figure 7. Example of demand-shift potential, Scenario 1, 2030



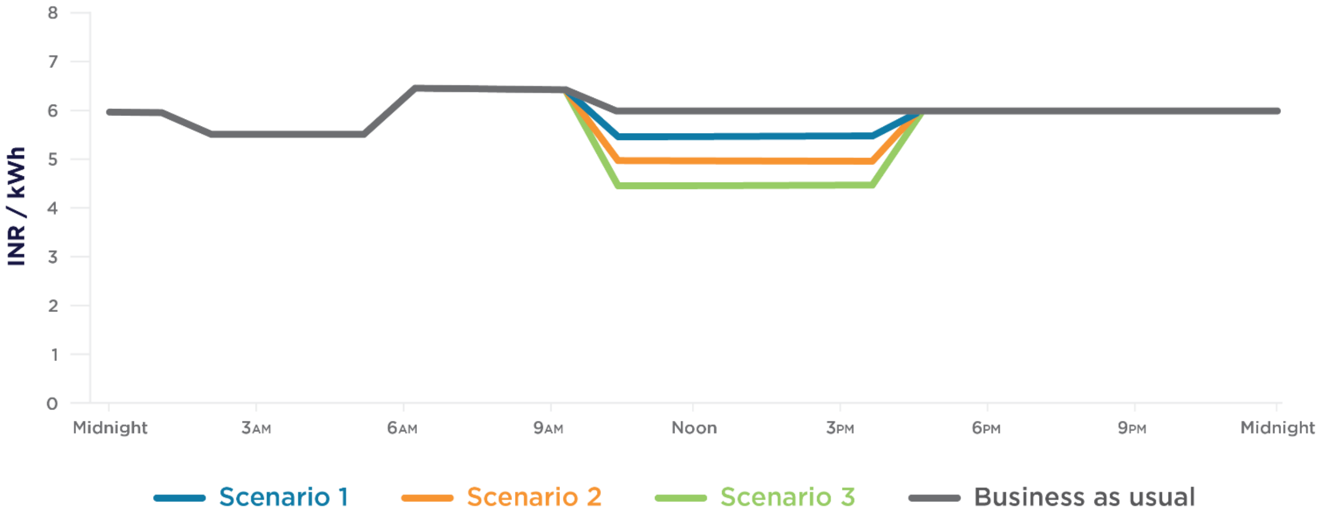
Data source: ICCT. (2024). [Unpublished raw data projecting potential demand shift to solar hours in 2030]

Figure 8[61] shows the EV tariffs in Scenarios 1-3 and the effect of rebates during solar hours that reduce the net cost of consumption during these hours. It also shows that tariffs (based on tariffs of Delhi utility Tata Power Delhi Distribution Limited) are otherwise relatively constant (compared to costs) at 6 INR/kWh for the entire day, with a 0.5 INR/kWh reduction around 3am-6am, and a 0.5 INR/kWh addition around 6am-9am.

[60] ICCT. (2024). [Unpublished raw data projecting potential demand shift to solar hours in 2030]

[61] MP Ensystems Advisory Pvt. Ltd., 2024.

Figure 8. EV tariffs, net of rebates (rebates grow with each scenario), INR/kWh

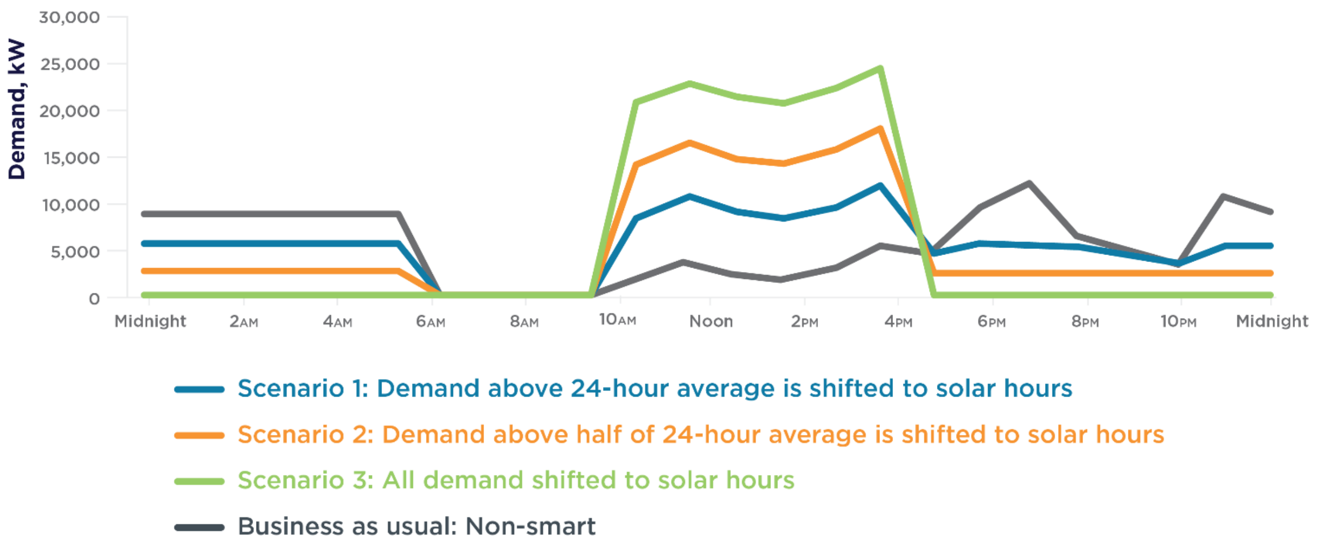


Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

These scenarios can be thought of as reflecting the costs of different levels of ambition in unlocking flexibility, where the costs of unlocking flexibility grow with the extent of flexibility to be unlocked.[62]

Figure 9[63] shows the assumed adjustment in e-truck charging demand patterns stimulated by the rebate, for sample year 2025. Smart charging scenarios show increasing volumes of demand shifted into solar hours as they grow in ambition. Other years follow similar patterns.

Figure 9. EV charging demand by scenario, 2025



Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

62 The modelling assumes that the business-as-usual tariff – built on observed tariffs in 2023 – does not change over the years, even as the cost to serve during solar hours falls over time with growing renewable penetration. Relaxing this assumption may offer a potential avenue for further research.

63 MP Ensystems Advisory Pvt. Ltd., 2024.

Change in utility profitability as a proxy of social benefit unlocked

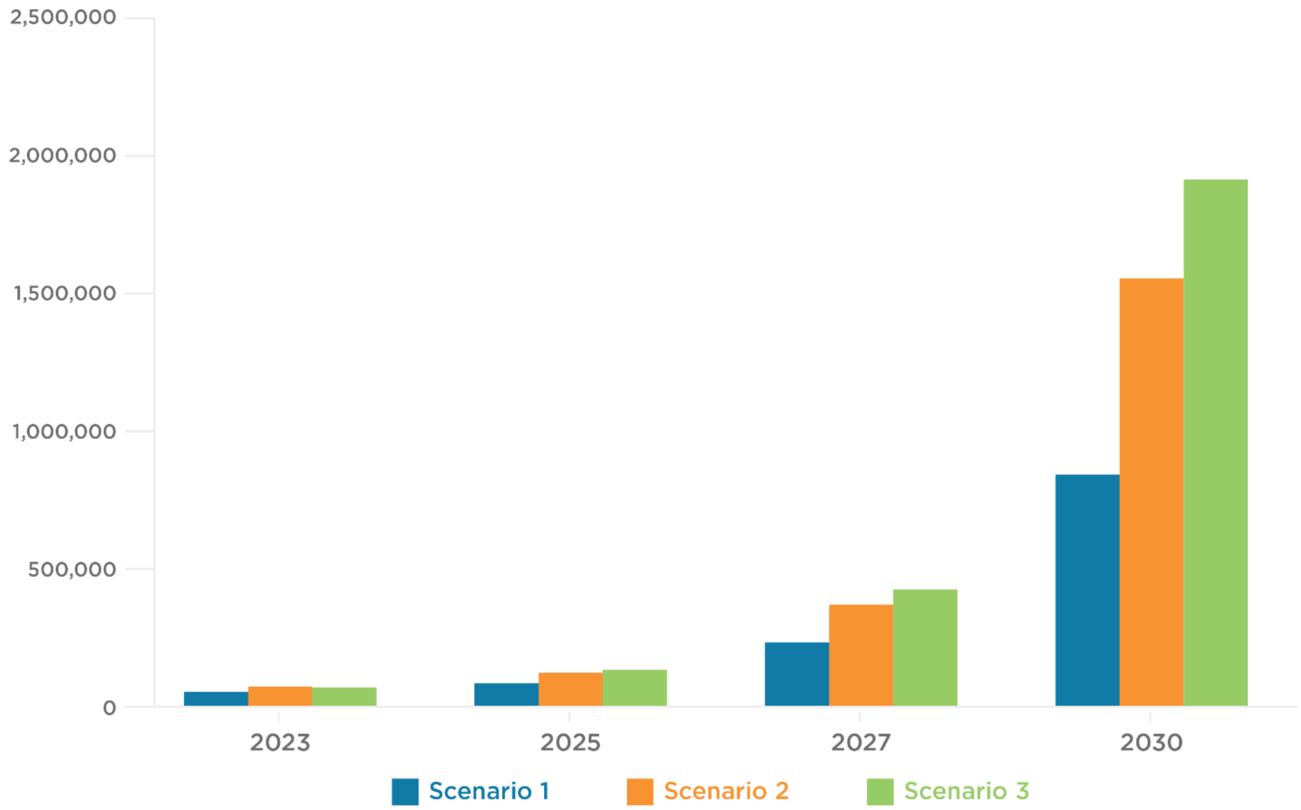
The key parameter of interest explored in the scenario analysis is the profitability of the utility. This parameter sheds light on the value unlocked by smart charging (in allowing the cheapest energy resources to replace more expensive coal energy during non-solar hours) after taking into account the assumed costs of stimulating demand-side flexing with rebates. This metric provides a first order approximation of the social value offered by smart charging, for any given (assumed) rebate, noting that business-as-usual tariffs are broadly flat, while cost to serve vary significantly during the day. As such the change in social welfare is substantially captured by the change in profitability of the utility. This value does not need to be retained by the utility, and could be shared with consumers, for example through lower tariffs, increasing the portion of social welfare captured by consumers.

Key findings

Cost savings

The scenario analysis suggests that the daily value of incorporating smartness in the e-truck charging system on the Jaipur-Delhi corridor could be from INR 0.8 million to INR 1.9 million by 2030, depending on the level of flexibility unlocked (Figure 10).[64]

Figure 10. Societal benefit of solar smartness (proxied by change in total profit of utility), INR/day



Data source: MP Ensystems Advisory Pvt. Ltd. (2024). *Smart Charging in India*

[64] MP Ensystems Advisory Pvt. Ltd., 2024. Note that given the level of uncertainty, discounting for time preference is not applied.

Annually this might amount to INR 300 million to INR 700 million (roughly US$ 3.6 million to US$ 8.4 million) by 2030.

What drives this result? Although the rebate reduces the profitability of each unit of energy sold (and consumed) during solar hours, the modelling still allows that the utility profit on energy sold during solar hours is greater than non-solar hours, and so the more demand that is modelled as shifted by a rebate into solar hours, the greater the utility profit. Particularly important assumptions therefore are the extent of demand shift assumed and the cost of this shift (the size of the rebate).

Emissions reductions

The associated reduction in carbon emissions — from displacing consumption of carbon intensive electricity with much cleaner predominantly-solar-powered electricity — are estimated to be about 300-900 tonnes per day by 2030, depending on the extent of flexibility unlocked by optimisation. This amounts to a saving of between 0.1 million to 0.3 million tonnes of carbon emissions per year.[65]

If e-trucks were placed along other similar corridors across India, then the introduction of smart charging across (for example) 12 of them (as provided for in Government plans) could unlock a reduction of between 1 million and 3.5 million tonnes of annual carbon emissions (scaling up the MP Ensystems estimate, assuming similar effects along other corridors). All of this points to the value and urgency of meeting the e-trucks challenge and of ramping up progress in decarbonisation efforts.

A caveat here is that the extent to which carbon emissions reductions can be attributed to the introduction of smart charging for e-trucks depends on the wider decarbonisation policy framework. In the case of India, the presence of a renewable purchase obligation to drive decarbonisation means that the attribution of carbon savings from e-trucks can be debated.[66]

[65] MP Ensystems Advisory Pvt. Ltd., 2024.

[66] In India, the portion of renewable carbon-free energy is determined in the electricity sector by the ‘renewable purchase obligation’. It mandates that all electricity distribution licensees purchase or produce a minimum specified quantity of their requirements from renewable energy sources. Thus, if non-smart charging dampens e-truck demand for renewable energy, then other ways of delivering the obliged renewable portion of total energy served must be found. Therefore, while a clear benefit of smart charging is in unlocking cost savings, there may be more debate as to the emissions savings that can be attributed to smart charging in the presence of a renewable portfolio obligation (or other policy like carbon emission allowance schemes) that dictates the decarbonisation trajectory. Perhaps the strongest case for attributing the value of carbon emissions reductions to reforms that enhance system flexibility like smart charging for e-trucks may be that in lowering the cost of decarbonisation, it may accelerate or help sustain the process.

Conclusions, recommendations and further research

Conclusions

There can be significant benefits from using smart e-truck charging to optimise generation resources

The scenario analysis presents different scenarios showing how smart charging can help e-trucks to help optimise deployment of generation resources and in so doing reduce social costs. Focusing on a Delhi-Jaipur case study, the scenario analysis suggests that benefits of smart charging could amount to INR 300 million to INR 700 million (US$3.6 million to US$8.4 million) annually by 2030. This could scale up significantly: implemented across a dozen such corridors, as planned by India's Ministry of Power,[67] annual social cost savings of INR 3.5 billion to INR 8.5 billion (US$45 million to US$100 million) could potentially be unlocked by 2030. This could also help reduce carbon emissions by as much as 1 million to 3.5 million tonnes across the dozen corridors. If a smart approach is applied, carbon emissions savings from electrification could be over twice as large as they would be with a non-smart approach.

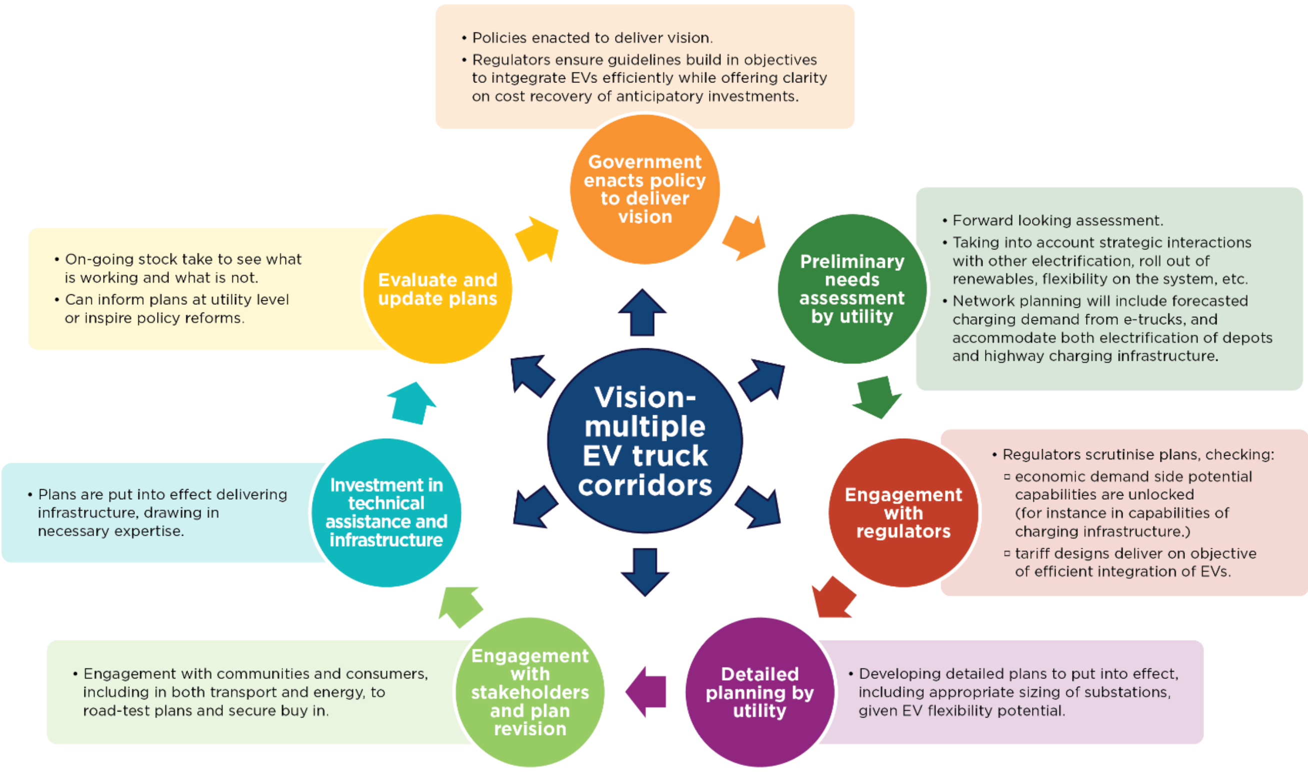
[67] The Ministry of Power has proposed 12 national corridors to be converted into e-highways. National Highways of Electric Vehicles. (n.d.) *About NHEV*. https://nhev.in/about-us-ev/

Recommendations

Strategically plan the efficient delivery of the e-trucks corridors

Strategic planning is necessary to unlock flexibilities that allow for speedy freight electrification at least cost. Figure 11 outlines multiple steps in this process. The recommendations that follow highlight a selection of these.

Figure 11. Strategic planning to deliver multiple e-truck corridors



Ensure smart EV charging is enshrined in policies and regulations

Opportunities for doing this might include in the Indian Bureau of Energy Efficiency's Draft Revised Guidelines and Standards for Electric Vehicle Charging Infrastructure.

Put into effect cost-reflective prices and tariffs to underpin smart charging

The extent of flexibility elsewhere in the system, of constraints on the network, and of renewables penetration all interact with each other, will change over time, and are largely unknowable in advance. This points to the importance of e-truck charging prices and tariffs reflecting marginal costs of wholesale production and of network constraints in a sufficiently accurate and granular way across both time and space. In response to these signals e-truck owners can compare the system value they unlock and appropriate by adjusting their consumption patterns with their private costs of doing so, and in pursuing their own interests will thereby serve the efficiency of the energy system.

In the short term, scalars or rebates can be used

These enable lower tariffs during hours of solar production (subject to limits of cost recovery). In this regard the gradual introduction of solar rebates for certain customer groups planned by the Ministry of Power are most welcome — and these could be accompanied by multi-part network tariffs reflecting demand contribution to the costs of meeting network peak.

In the longer term this implies a goal of introducing market-based prices

This means allowing real-time wholesale prices to shape the offer of energy to EV consumers, with a robust carbon price, and capturing network effects in locationally formed prices will ideally enable lower tariffs during hours of solar production (subject to limits of cost recovery).

Further research and caveats

This scenario analysis points to multiple opportunities for further research, including:

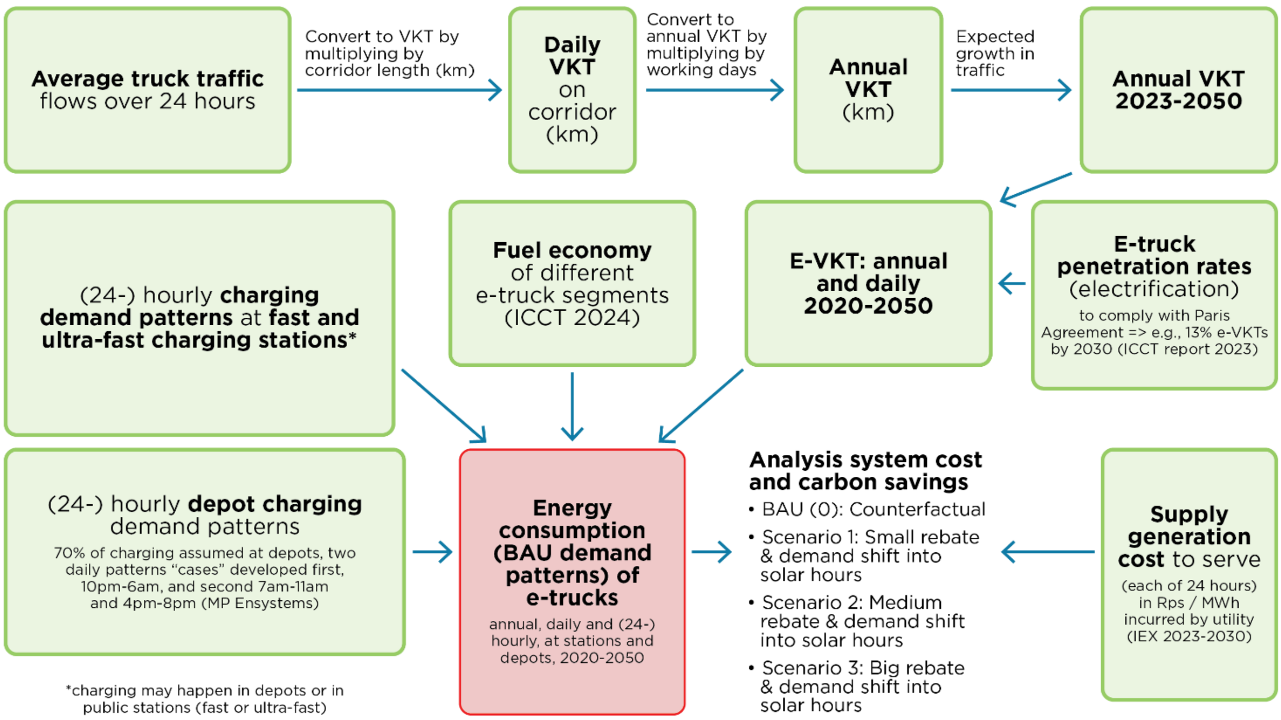
- The flexibility potential of electric freight, taking into account factors including transport behaviour, fleet driving patterns and traffic restrictions.
- The costs e-truck drivers incur in flexing their demands while meeting their needs, and the actual responsiveness of e-truck drivers to price signals (so that future research need not use scenarios of expected responsiveness, as have been employed in this study).
- Circumstances under which smart charging for e-trucks reduces the need for grid build. Although this analysis did not focus on the role of smart charging to alleviate grid constraints, the assumption that the grid will always be sufficient to accommodate e-trucks and variable renewable production may come under increasing strain as both are rolled out.
- Capturing within modelling the extent to which tariffs (more broadly across the economy) may change according to a shift in generation patterns associated with a shift in generation mix over time.
- Modelling the interaction between the ‘cost of serving’ metric (generation costs — ideally marginal, not average) and the adjustment of demand patterns.
- Modelling the impact on the number of chargers deployed to meet demand and the associated cost as demand patterns shift, and further insight on depot charging.

Annex

Modelling of charging demand

MP Ensystems' analysis of the potential impact of smart charging built on the development of business-as-usual demand patterns prepared by ICCT. This technical annex outlines the work of ICCT to derive business-as-usual (non-smart) energy consumption patterns of e-trucks; this is the work that precedes and contributes to the box highlighted in red in the Figure 12 overview of the analytical approach.

Figure 12. Analytical approach (note 'BAU' means business-as-usual, VKT means vehicle kilometres travelled)



Estimation of charging needs

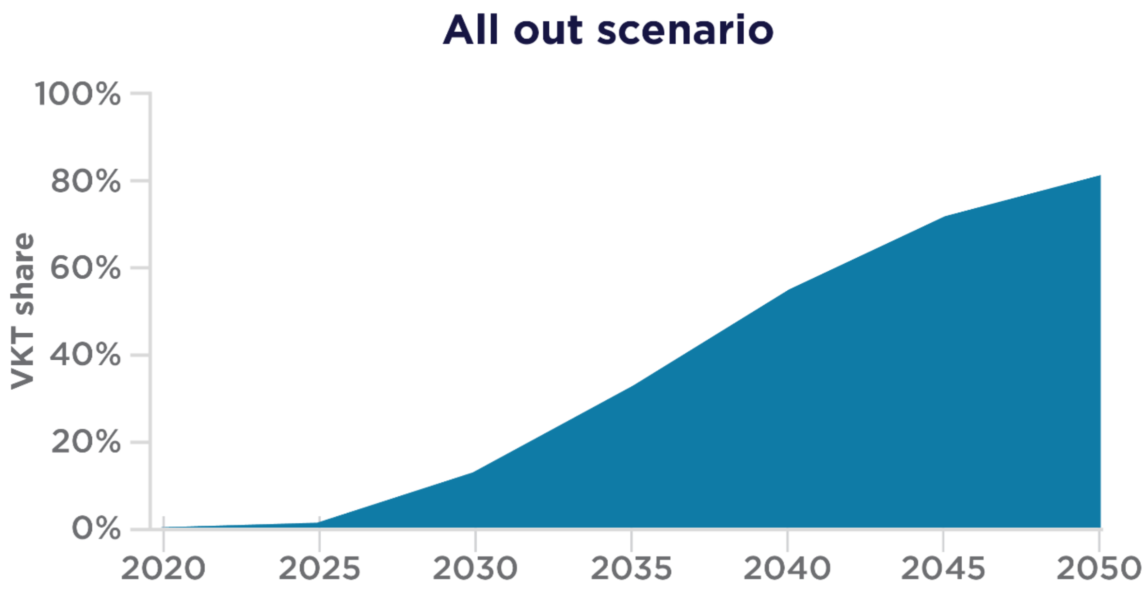
ICCT models charging needs of e-trucks on the Delhi-Jaipur corridor using previously documented ICCT modelling methods.[68] E-truck penetration rates are modelled for the 'all-out' scenario where 100% e-truck sales are achieved by 2045 to comply with the sub-2°C

68 Ragon, P.L., et al. (2023, May). *Near-Term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States*. ICCT. https://theicct.org/publication/infrastructure-deployment-mhdv-may23/.

warming goal by 2050 under the Paris Agreement.[69] This translates to 13% electric vehicle kilometres travelled (e-VKTs) by 2030, 54% by 2040 and 80% by 2050 (see Figure 13).[70]

ICCT applied these e-VKTs to truck traffic surveyed at three toll plazas on the Delhi-Jaipur corridor (Kherki, Shahjahanpur and Daulatpura). ICCT further used the battery sizes and fuel economy for e-truck segments from ICCT research[71] simulating the fuel economy of e-trucks on Indian drive cycles, to obtain the energy consumption of e-trucks on this corridor.

Figure 13. Electric VKT share in the total truck VKTs on Delhi-Jaipur corridor through 2050



Data source: ICCT. (2024). [Unpublished raw data of energy consumption by e-trucks on the Delhi-Jaipur corridor]

Table 3[72] below shows combinations of three kinds of chargers — (i) overnight, (ii) fast, and (iii) ultra-fast chargers — considered in the analysis according to different battery size. Overnight and fast chargers are the commonly deployed chargers in India. Based on stakeholder interviews, ICCT assumes ultra-fast chargers (500 kW nominal power rating) are deployed from 2030 onwards. A previous study on e-truck driving patterns on the same corridor finds that 70% of trucks make round trips.[73] Thus, it is assumed here that 70% of charging happens overnight at depots, and the remaining 30% happens at public chargers, largely with fast (though with some ultra-fast) chargers in the period to 2030.

69 Sen, A. & Miller, J, 2023, September.

70 ICCT. (2024). [Unpublished raw data of energy consumption by e-trucks on the Delhi-Jaipur corridor]

71 Kaur, H., Yadav, A. and Deo, A. (in press). *Total Cost of Ownership Parity between Battery-Electric Trucks and Diesel Trucks in India*. ICCT.

72 ICCT. (2024). [Unpublished raw data comparing three kinds of chargers according to battery size]

73 Office of the Principal Scientific Adviser to the Government of India. (2023, November). *Technology Assessment of Zero-Emission Trucking on the Delhi-Jaipur Corridor*. https://psa.gov.in/CMS/web/sites/default/files/psa_custom_files/Delhi%20Jaipur%20Highway_311023_Without%20Blank%20%282%29.pdf

Table 3. Combinations of chargers considered

Segment	Battery in 2023	Overnight charger	Fast charger	Ultra-fast charger
3.5t to 7t	120 kWh	22 kW	120 kW	–
7t to 12t	218 kWh	22 kW	120 kW	–
12t to 16t	241 kWh	60 kW	120 kW	–
16t to 25t	337 kWh	60 kW	120 kW	–
25t and above	657 kWh	120 kW	240 kW	500 kW
HDCT	1,064 kWh	120 kW	240 kW	500 kW

Data source: ICCT. (2024). [Unpublished raw data comparing three kinds of chargers according to battery size]

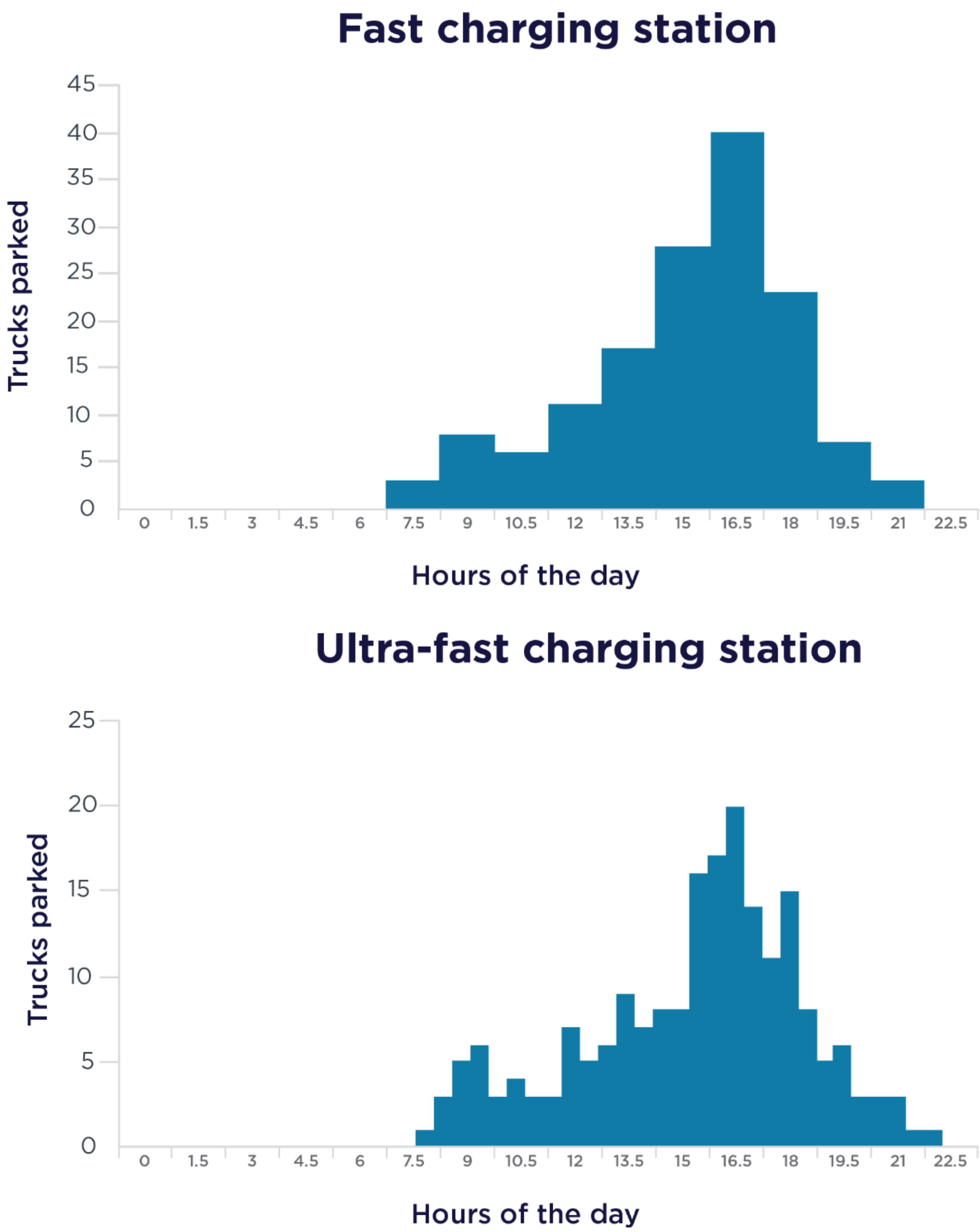
Primary surveys of e-truck drivers were conducted to understand driving patterns — distance travelled per day, time spent at rest stops, time of entry and exit at rest stops. This data was used to inform utilisation assumptions for charging stations — that all the chargers observe one charging session per day in the initial years, starting 2023, and then grow logarithmically to maximum utilisation rate by 2040 (assuming a five-year lag with Europe and the United States).

ICCT uses data gathered through primary interviews on parking patterns to estimate the maximum utilisation rate at a fast charging station and an ultra-fast charging station. ICCT therefore employs the assumption that each fast charging session is 1.5 hours long, sufficient to top-up with the batteries and ranges on the corridor, and within the average time spent by truckers at rest stops (2 hours). In the case of ultra-fast charging stations, ICCT assumes each charging session is 30 minutes long. ICCT uses e-truck parking patterns from survey data to develop two baseline parking profiles, one for the fast charging station and the other for the ultra-fast charging station (see Figure 14).[74] Based on these profiles, ICCT estimates the maximum daily utilisation rate of 5.5 hours or 23% for the fast-charging station, and 5 hours or 21% for the ultra-fast charging station.[75]

[74] ICCT. (2024). [Unpublished raw data comparing e-truck parking patterns at fast charging and ultra-fast charging stations].

[75] On average, given current driving and resting patterns of truck drivers, chargers can be used only 5.5 hours a day (23% of the day), even if 100% of the trucks are electric. This affects the number of chargers required. The higher the daily utilisation rate, for example, the lower the number of chargers needed: the chargers are engaged for more hours in the day because the arrival of the trucks at the rest stops is not concentrated (in the evening) and is uniform throughout the day. The more that truck resting periods at rest stops are concentrated in the evening, the lower the utilisation rate, and the greater the number of chargers needed to cater to that peak in the evening.

Figure 14. Parking profiles of e-trucks at the fast charging station and the ultra-fast charging station (public daytime charging only — excludes depot charging, much of which happens at night)

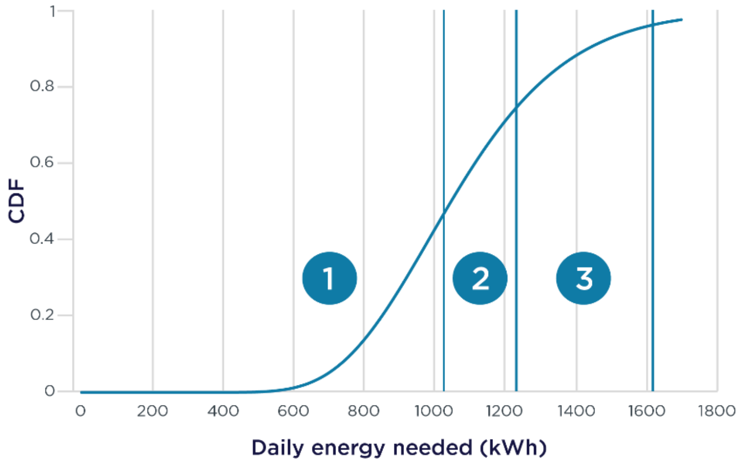


Data source: ICCT. (2024). [Unpublished raw data comparing e-truck parking patterns at fast charging and ultra-fast charging stations].

ICCT designs charging pattern configurations based on the battery size and energy demand of each vehicle segment. ICCT assumes that the e-trucks start their trips with a fully charged battery, and thus overnight charging caters to most of the energy needs of e-trucks, topped up with fast charging for trucks that need additional energy for the more-than-average distances travelled. Figure 15[76] shows the sample charging pattern of a tractor trailer[77] on the Delhi-Jaipur corridor. Tractor trailers that need about 1,000 kWh of energy per day will rely on overnight chargers either at depots or public locations. Tractor trailers that need more than 1,000 kWh of energy up to 1,200 kWh are modelled as starting with a fully charged battery from a depot charger, and then topping-up their batteries at the fast charger en route. For those with energy demand exceeding 1,200 kWh, the tractor trailer will have to make two stops en route to top up batteries. For context, the primary survey with e-truck drivers shows that they typically make two or three stops on the Delhi-Jaipur corridor during their journey.

Figure 15. Charging patterns (cumulative density function) considered for the tractor trailer

Year	Priority	Configuration
2023	1	(1) Overnight
	2	(1) Overnight + (1) Fast
	3	(1) Overnight + (2) Fast
2030	1	(1) Overnight
	2	(1) Overnight + (1) Ultra-fast
	3	(1) Overnight + (1) Fast + (1) Ultra-fast



Data source: ICCT. (2024). [Unpublished raw data displaying a sample charging pattern for a tractor trailer based on daily energy needed].

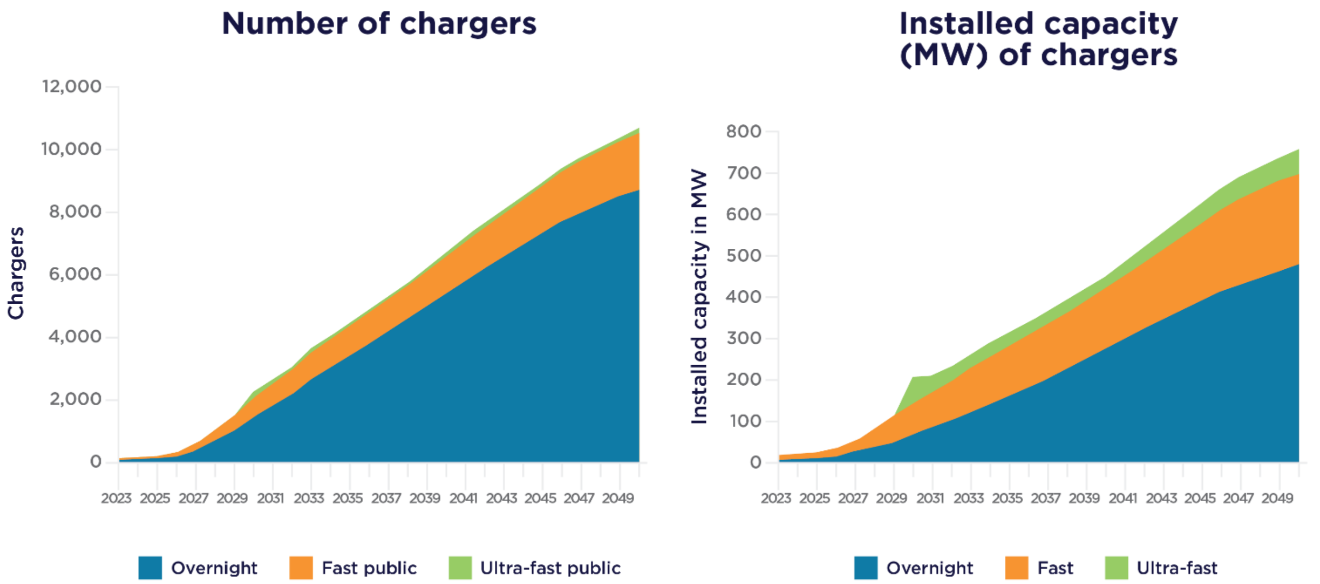
Combining these inputs and assumptions, ICCT estimates the charging needs and the installed power capacity of chargers needed along the corridor. Figure 16[78] shows the number of chargers required through 2050 along the Delhi-Jaipur corridor, in the scenario where 100% of e-truck sales is reached in 2045. The second chart shows the installed capacity of chargers needed by 2050 to cater to e-trucks traversing the corridor.

76 ICCT. (2024). [Unpublished raw data displaying a sample charging pattern for a tractor trailer based on daily energy needed].

77 Tractor trailers, also called semi-trucks, or HDCT, are one segment of trucks. They are usually the heaviest trucks.

78 ICCT. (2024). [Unpublished raw data projecting the charging needs and the installed power capacity of chargers needed along the Delhi-Jaipur corridor]

Figure 16. Number of chargers and the total installed capacity of the chargers needed on the Delhi-Jaipur corridor through 2050



Data source: ICCT. (2024). [Unpublished raw data projecting the charging needs and the installed power capacity of chargers needed along the Delhi-Jaipur corridor]

100% e-truck sales by 2045 translates into 73% e-trucks in the total stock of registered vehicles traversing the Delhi-Jaipur corridor. To cater to such a large trucking fleet, about 204 MW installed capacity of chargers are needed by 2030, a number which would grow by nearly four times by 2050 (760 MW).

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