Office of the Principal Scientific Adviser
to the Government of India

TECHNOLOGY ASSESSMENT OF ZERO-EMISSION TRUCKING ON THE DELHI-JAIPUR CORRIDOR

November, 2023

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List of Abbreviations

BET: Battery Electric Truck

CAPEX: Capital Expenditure

CNG: Compressed Natural Gas

CO2: Carbon Dioxide Emissions

DISCOMs: Distribution Companies

GDP: Gross Domestic Product

GVWR: Gross Vehicle Weight Rating

H2: Hydrogen

FCET: Fuel Cell Electric Truck

ICE: Internal Combustion Engine

HDT: Heavy Duty Truck

MDT: Medium Duty Truck

NOx: Nitrous Oxide

NH: National Highway

SoC: State of Charge

SoH: State of Health

PM: Particulate Matter

TCO: The total cost of ownership

VKT: Vehicle Kilometers Travelled

ZET: Zero-emission trucks

Executive Summary

The logistics sector is the backbone of the economy as it ensures the streamlined flow of goods for people and businesses. With the increase in population and gross domestic product (GDP), cumulative freight volume is expected to grow four times by 2050, with the trucking sector representing 70% of domestic freight movement.[1] With the growing demand for goods, it is imperative to deploy zero-emission trucks (ZETs), such as battery electric trucks (BETs), hydrogen fuel cell electric (FCET), and hydrogen internal combustion engine (ICE) trucks, to chart a resource-efficient growth trajectory and support improved logistics efficiency, lower costs, better air quality, reduced environmental impact, and enhanced public health.

Recognizing the economic and ecological advantages of ZETs, nations are shifting away from fossil fuel-based trucks. By scaling up the adoption of ZETs, India can distinguish itself in the global market. ZET corridor(s), segments of highways equipped with infrastructure for refueling ZETs, play a pivotal role in concentrating investments to achieve economies of scale in ZET adoption, facilitating ZET technology trials, and bolstering market confidence. Corridors enable fleet operators and businesses to test various technologies and evaluate the viability of ZETs, assist manufacturers in efficiently scaling up production by aggregating demand, and enable financiers to streamline investment without significant capital outlays. However, various ZET technologies are available in the market that can be deployed on these corridors.

This report utilizes the Delhi-Jaipur corridor as a potential "lighthouse" corridor to evaluate the cost, viability, and operability of different ZET technologies. It assesses seven different infrastructure technologies – 1) fast chargers, 2) ultra-fast chargers, 3) battery swapping, 4) catenary, 5) dynamic induction, 6) Hydrogen FCET, and 7) Hydrogen ICE. The cost and feasibility of these seven ZET technologies are analyzed for two deployment timeframes: a pilot project involving the deployment of 100 trucks by 2025 and a scaled deployment with 5,500 trucks in operation by 2030.

The cost analysis presents the per-vehicle and total costs required to pilot and scale ZET deployment along the Delhi-Jaipur corridor, including vehicle, charging, refueling infrastructure, and requisite grid upgrade costs. Investment risks are elaborated upon in the performance, technology, and market assessment section, which offers insights into the viability of each technology. In addition to the hard costs assessed these performance parameters must also be factored into public and private decisions making. The report ends with a roadmap tailored for decision-makers, providing technology and market-specific considerations, techno-economic analysis, and an operational viability assessment of seven distinct ZET technologies and associated infrastructure.

In addition to technology cost, this report also outlines advantages, potential drawbacks, and idealized use case scenarios across different trucking technologies. Key considerations are captured below:

Figure 1: The operational benefits, costs, and ideal use cases of ZET technologies

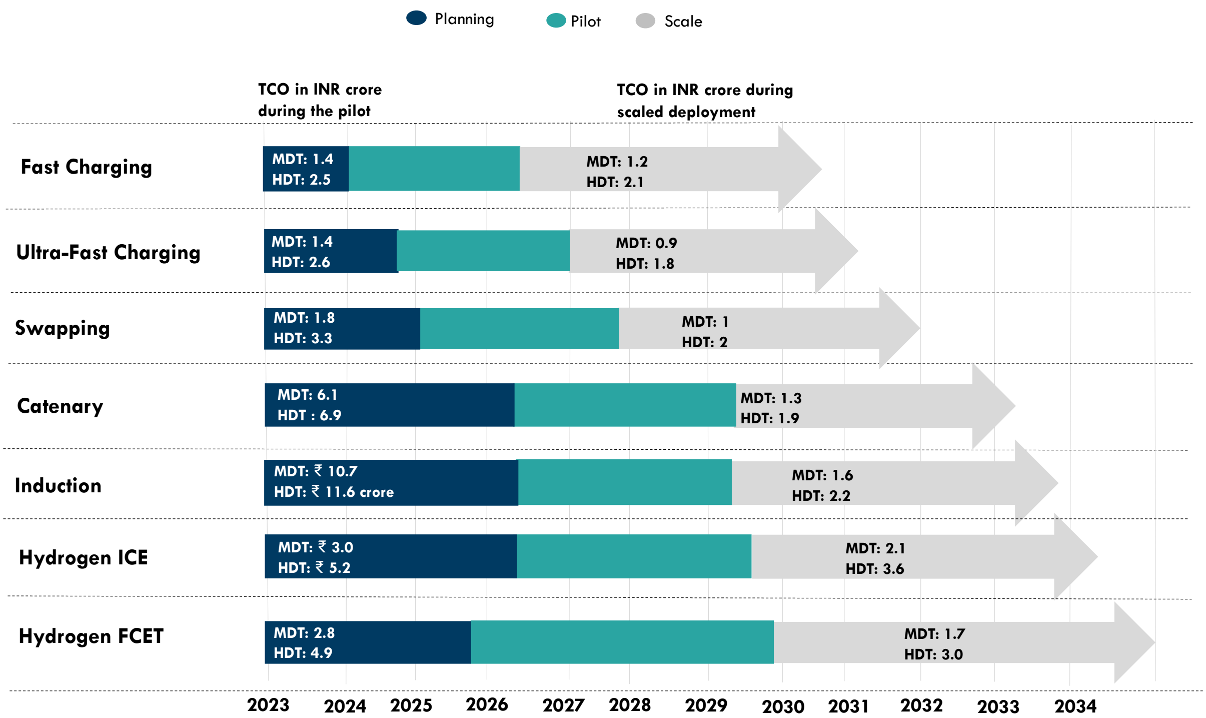
Technology	Pros	Cons	*Pilot deployment cost (Crore INR)	**Total deployment cost (Thousand Crore INR)	Ideal-use case applications along the Delhi-Jaipur corridor
Fast Charging	Manageable charging schedules, high technology readiness level, refueling time is often greater than 3 hours	Lesser payload due to large battery, higher charging downtime as refuelling time is often greater than 3 hours	195	9.5	Fleets with overnight depots, routes with set origin and ending destinations, and readily available downtime for charging. This technology can cater to volume-constrained loads like white goods and auto parts.
Ultra-Fast Charging	Faster refueling times than fast charging can be deployed incrementally to meet truck demand, refueling time can range from under an hour to up to 2 hours or more	High electricity peak demand and high associated grid costs	204	8.4	Highly travelled trucking corridors where infrastructure can have high utilization and there is enough upstream power availability. This technology can cater to volume-constrained loads like white goods and E-Commerce.
Swapping	Refueling time is under 10 minutes, manageable peak loads	High spare battery cost, requires battery standardization for scalability	257	9.4	Fleets conduct frequent trips under closed-loop systems, and limited downtime available for charging. Catering to volume-constrained loads like white goods, E-Commerce and auto parts
Catenary	Ability to limit downtime due to en-route charging, smaller battery packs, and batteries are charged in motion hence there is no allotted refueling time	Uncertainty regarding infrastructure CAPEX and OPEX, technology-lock-in, low technology readiness level	651	8.2	Fleets deployed along short, closed-loop corridors near infrastructure catering to heavy loads like construction aggregates
Induction	Ability to limit downtime due to	Limited real-world	1118	9.1	Fleets deployed along short, closed loop corridors

	en-route charging; smaller battery packs; batteries are charged in motion hence there is no allotted refueling time	demonstrations. Uncertainty regarding infrastructure CAPEX and OPEX, technology-lock-in, low technology readiness level			near infrastructure catering to heavy loads like construction aggregates
H2 ICE	Lowest vehicle purchase cost, minimal penalty on the payload for applications like bulk goods, refueling time is under 10 minutes	High fuel costs, still emit NOx, not suitable for loads requiring large volumetric space, nascent technology with limited demonstrations	411	17.5	Fleets travelling long distances which require minimal downtime and cater to heavy bulk loads like construction aggregates, blue metal, cement, etc.
H2 FCET	Minimal penalty on the payload for applications like bulk goods, refueling time is under 10 minutes	High fuel cost and high vehicle purchase cost, not suitable for loads requiring large volumetric space, nascent technology with limited vehicle model availability	387	15.2	Fleets travelling long distances which require minimal downtime and cater to heavy bulk loads like construction aggregates, blue metal, cement, etc.

** Pilot deployment cost is defined as the total cost of deploying 100 ZETs and requisite refueling and grid infrastructure.*
***Total deployment costs are defined as the cost of deploying 5,500 ZETs and requisite refueling and grid infrastructure by 2030; this cost figure does not include soft costs such as permitting, site assessment fees, and costs associated with potential construction delays, as these are highly project-specific and cannot be modeled with certainty.*

When planning ZET deployment and infrastructure development, it is essential to take into account the planning timeframe and the level of maturity of the technology solution, as these factors will impact the time horizon of initiating a pilot and ultimately scaling ZET deployment along the Delhi-Jaipur corridor. Figure 2 highlights the tentative timeframe for pilot and scaled deployment of various ZET technologies based on the cost, performance, technology, and market maturity parameters.

Figure 2: The total cost of ownership for MDT and HDT ZETs and the time to market associated with the seven differing ZET technologies.



Note: The differing phases of deployment (planning, pilot, scale) are represented by different colors and correspond with the year that a given technology can reasonably be deployed through a pilot demonstration and scaled; the timelines are derived based on technology readiness, production capacity today, and market maturity based on insights gathered in stakeholder interviews. The two cost figures represent the respective cost to deploy ZETs via each unique technology at pilot (100 ZETs and associated infrastructure) and at scale (5,500 ZETs and associated infrastructure) expressed as a per truck total cost.

Considering the evolving ZET market, ongoing research, and diverse industry demands, it is essential to recognize that a single ZET technology will not suffice to cover the entire trucking market. To harness the synergies of multiple ZET technologies, it is crucial to carefully select and match them to specific use cases while promoting interoperability between trucks and their batteries. Through these synergies, governments and private actors can strike a balance between deploying new infrastructure assets that meet operational requirements, minimizing vehicle downtime, maintaining connectivity and avoiding over-spend and technology lock-in. Simultaneously, they can realize the near-term benefits of ZET adoption, such as fuel savings and improved air quality. Ultimately, this report aims to support the design of a roadmap for a ZET corridor and seeks to catalyse the design of a roadmap for a ZET corridor and assist governments and industries in policymaking and business decision-making to scale ZET deployment in India.

Introduction

India is currently experiencing a historic surge in freight demand, driven by urbanization, population growth, and the rise of e-commerce. India moves a staggering 4.6 billion tonnes of freight annually, resulting in over three trillion tonne-kilometers of freight demand. Despite trucks accounting for just 3% of the total vehicle fleet including passenger and freight vehicles, they contribute 34% of carbon dioxide (CO^2) emissions and 53% of Particulate Matter (PM) emissions.[2] As freight demand rises, reliance on fossil fuel vehicles will perpetuate negative externalities, including air pollution, threats to public health, escalating transportation costs, and energy security concerns.

Amid the global shift towards zero-emission vehicles, India is making substantial progress in decarbonizing its transportation sector, particularly in the realm of two-, three-, and four-wheelers and light-duty vehicles. A sector-wide transition to ZETs can offer numerous public benefits that align with India's national priorities:

- *Logistics cost savings:* ZETs present an opportunity for a 17% reduction in logistic costs. These cost savings can directly reduce the cost of end goods and commodities, benefiting the public and society.[3]

- *Enhanced energy Security:* ZET adoption can help India chart a path toward greater energy security. Road freight accounts for more than 25% of annual oil imports. ZET adoption can reduce oil spending by 993 billion liters of diesel cumulatively by 2050, resulting in upwards of ₹161 lakh crore of reduced oil expenditures. [4]

- *Alignment with Atmanirbhar Bharat (Self-Reliant India):* The creation of a ZET market in India supports national priorities. By 2050, ZETs could create a cumulative battery demand of up to 5,400 GWh in India, providing the impetus for India to become a low-cost, low-carbon manufacturing hub.[5]

- *Improved air quality and lower carbon emissions:* ZETs have no tailpipe emissions and can reduce PM and nitrous oxide (NOx) pollution by over 50% by 2050, substantially improving air quality and public health. [6] ZET adoption can lead to dramatic emission reductions in the transport sector, supporting India's five central climate goals (Panchamrit). Replacing diesel trucks with ZETs could eliminate up to 3.8 gigatonnes of carbon emissions between now and 2050. [7]

The transition towards ZETs can be unlocked by deploying ZET corridors and highways equipped with the necessary charging or refueling infrastructure to facilitate travel. ZET corridors can work to channel investment and offer operators a route that can seamlessly support ZET travel. ZET corridors can be used in the following manner to spur ZET adoption.

- *Build market confidence*: ZET corridors allow fleet operators to assess the techno-economic feasibility of ZETs. By providing the necessary refueling infrastructure, fleet operators can evaluate how ZETs meet their freight demands in real-world conditions. This helps instill market confidence in the viability of ZETs and can encourage further adoption.

- *Scale production*: ZET corridors aggregate the demand for ZETs, providing valuable insights into the market's requirements and preferences. With concentrated demand, manufacturers can efficiently scale up production and meet the growing need for ZETs, leading to increased availability and affordability.

- *Risk Mitigation*: By concentrating investments along dedicated corridors, stakeholders can effectively pool resources, reducing the risks associated with large-scale implementation. This approach allows for iterative improvements and technological advancements in a controlled environment.

- *Knowledge sharing*: Valuable insights and data acquired from ZET corridors can be extrapolated and applied to accelerate ZET adoption on a larger scale. The information gained from these corridors can be shared with policymakers to design effective regulations, incentives, and policies that further promote the transition to zero-emission transportation.

At present, 50% of the truck traffic in India travels along seven highway corridors connecting Delhi, Mumbai, Chennai, Kandla, Kochi, and Kolkata. [8] The significant volume of road freight and economic activity on these corridors presents a strategic opportunity for investing in charging or refueling infrastructure development across the entire road network to accelerate the adoption of ZETs.

Among these highly-traveled corridors, the Delhi-Jaipur corridor stands out. This eight-lane highway connects two prominent cities in Northern India and serves as the initial link along the more extensive Delhi-Mumbai corridor. [9] Furthermore, due to its significant freight volumes, suitable length (280 km), and robust grid infrastructure, the Delhi-Jaipur corridor presents ideal circumstances for a flagship ZETs corridor.

This report aims to evaluate the cost-effectiveness and feasibility of various ZET technologies for the Delhi-Jaipur corridor. The report analyzes the variation in the cost of vehicles and charging infrastructure across different technologies. The subsequent section assesses ZET technology operations and performance, comparing market conditions based on deployment timelines, market maturity, skill development needs, and the risk of technology lock-in. Finally, the report concludes by outlining actionable steps for initiating a ZET pilot project along the Delhi-Jaipur corridor and presents a strategic framework for the widespread deployment of ZET technology.

Background

Overview of the Delhi-Jaipur Highway

The Delhi-Jaipur corridor is a crucial link for economic and industrial activities in Northern India. This 280 km long corridor is an important segment of National Highway (NH) 48, connecting Delhi and Mumbai – one of the four Golden Quadrilateral highways.[10] The corridor is highly suitable for ZET deployment for several reasons. Firstly, the distance between Delhi and Jaipur falls within the range of ZET models available in the global market today and this regional corridor would offer an operational proof point of ZETs in the Indian market.[11] Secondly, both Delhi and Jaipur host industrial clusters and are planning the development of multimodal logistics parks, making the corridor a central hub for freight aggregation and distribution.[12] Finally, transmission and distribution systems run parallel to the Delhi-Jaipur corridor, ensuring a robust grid infrastructure and adequate power capacity for truck charging.[13]

The Delhi-Jaipur highway facilitates the flow of a variety of goods and multiple use cases, including:

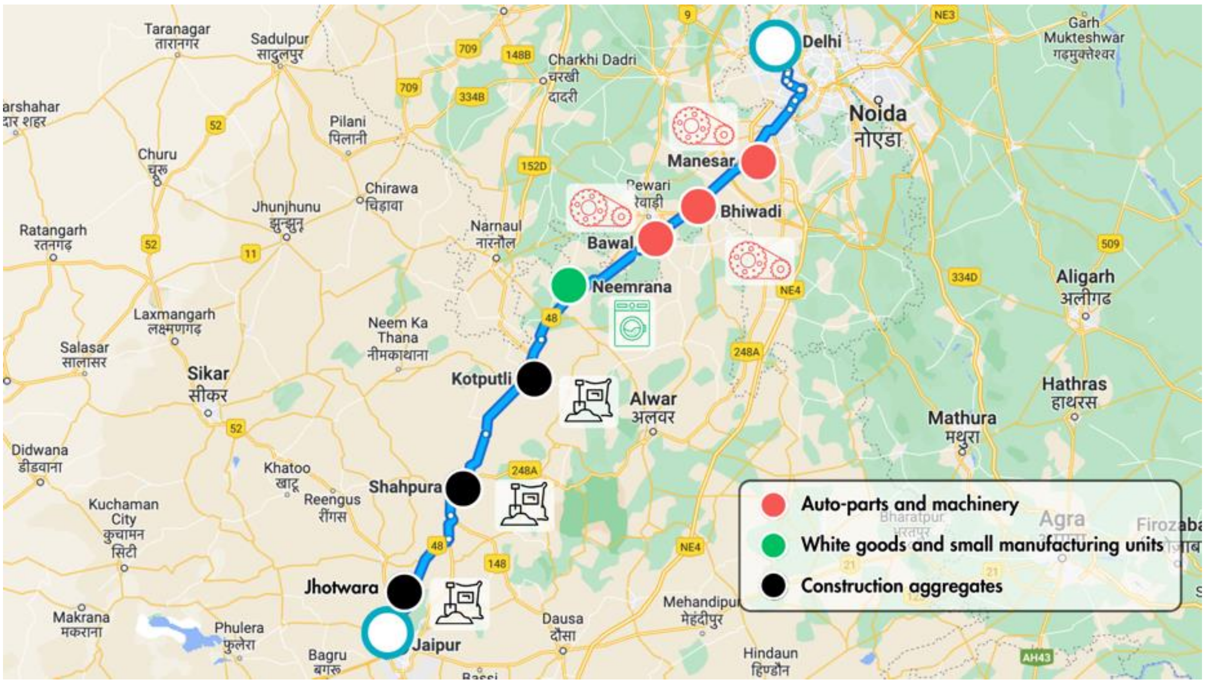
- *Industrial goods:* Auto parts and white goods are manufactured in major industrial hubs like Neemrana, Bhiwadi, and Bawal. Auto parts are primarily transported to Gurgaon and Delhi for use by automobile companies, while white goods are shipped to both Delhi and Jaipur.

- *Construction aggregates and blue metal:* Construction aggregates and blue metal, are primarily sourced from Kotputli and are transported to the Gurgaon region. Such trips involve frequent truck travel with minimal downtime.

- *E-Commerce containerized movement:* E-commerce is significant along the Delhi-Jaipur highway due to strong consumer demand. This distribution follows a hub-and-spoke model, where Delhi/Gurgaon serves as a central hub for various e-commerce companies, and Jaipur functions as one of the satellite locations or spokes in this network.

- *Fresh produce:* Fresh produce, such as fruits and vegetables, is a common commodity transported along this corridor, with frequent overnight shipments from Jaipur to Delhi.

Figure 3: Industrial clusters along the Delhi-Jaipur corridor

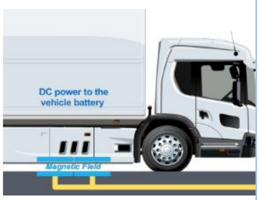


The highway sees an equal mix of medium-duty trucks (MDTs) below 12 tonnes and heavy-duty trucks (HDTs) above 12 tonnes, each serving different purposes. MDTs primarily transport fresh produce and some industrial goods. HDTs are divided into two categories: those with a gross vehicle weight rating (GVWR) of 18 tonnes or more, carrying 32ft containers for e-commerce and industrial goods, and heavy-duty tractor trailers with a 55-tonne GVWR, mainly used for transporting bulk products like construction aggregates. While some trucks travel to and from Delhi or Jaipur, most travel to and from one of the three industry clusters near Bhiwadi, Neemrana, or Kotputli. Diesel is the most commonly used fuel for these trucks, but many MDTs are switching to compressed natural gas (CNG) to save on the Environmental tax imposed by the National Green Tribunal when entering Delhi.[14]

ZET Technologies under consideration

This paper assesses the costs and viability of deploying different ZET technologies along the Delhi-Jaipur corridor. The seven ZET technologies covered in this paper are described in the figure below.

Figure 4: The seven ZET technologies were assessed in this study

Technology		Description
Fast charging (at depots)		Battery electric trucks are charged via plug-in 100kW depot chargers.[1] Fast Charging at depots typically occurs overnight at truck charging depots when the trucks are not in operation.
Ultra-Fast Charging (en-route)		Ultra-fast charging technology recharges battery electric trucks using high-power plug-in chargers with power levels ranging from 240kW to 500kW, typically en-route and in relatively short periods. Ultra-fast charging stations are typically installed along highways, allowing trucks to charge during their operational hours.
Battery swapping		Swappable charging stations are equipped with removable batteries that can be mechanically swapped and replaced at swapping stations within 5-10 minutes. The depleted batteries are then recharged at swapping stations using 300kW chargers.
Catenary		Battery electric trucks equipped with a pantograph, a mechanical device mounted on the top of the truck, can draw current from contact with overhead catenary wires. Overhead catenary wires running parallel to the highway segment charge the truck while it is in motion.
Dynamic Induction charging		Battery electric trucks receive power through electromagnetic fields via underground coils. For dynamic induction charging dynamic induction infrastructure is installed under the highway in multiple-kilometre stretches, allowing the vehicle to charge en-route.[2]
Hydrogen Internal combustion Engine (ICE)		Hydrogen ICE refers to trucks with internal combustion engines powered by hydrogen and refueled at hydrogen stations. These trucks do not have on-board lithium-ion batteries.

[1] 100kwh is the size of depot chargers utilized in this analysis based on the truck charging time see appendix c for more details

[2] Inductive charging can be deployed in two primary manners: in modules, where the truck charges while stationary, or via Dynamic Induction tracks or inductive loops installed under the road surface to facilitate charging while in motion. This report considers the deployment of the latter.

Hydrogen fuel cell electric truck (FCET)		A hydrogen FCET is equipped with lithium-ion batteries, a fuel cell system, and a hydrogen storage tank, using hydrogen as its primary energy source. It is refueled at hydrogen refueling stations.

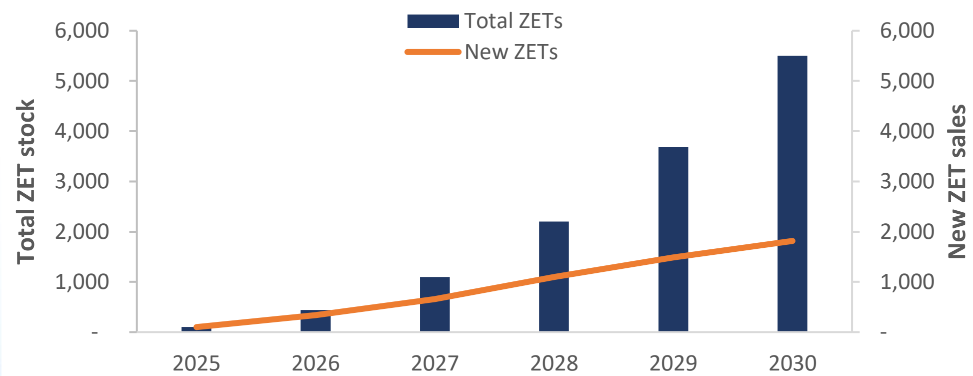
ZET deployment projections

The cost and feasibility of the seven ZET technologies listed above are analyzed for two differing timeframes:

1. *Pilot in 2025:* In the pilot case, the model depicts the costs of deploying 100 trucks along the Delhi-Jaipur corridor by 2025 and considers market prices expected in 2025.[15]
2. *Scaled deployment by 2030:* In the scaled deployment, the model assumes the deployment of 5,500 ZETs on the corridor by 2030, depicts the costs and presents forward-looking costs in 2030.[16]

The figure below outlines new and cumulative ZETs in the pilot and scaled deployment. At the pilot scale, a number of fixed 100 trucks was taken to derive cost figures. The scaled deployment truck figure was derived from analyzing the toll data from the Indian Highway Management Company Limited (IHMCL) and insights gathered from expert interviews with OEMs, dealerships, transporters, shippers, and industry players. Based on these assessments, it was estimated approximately the stock of trucks traversing the Delhi-Jaipur corridor is 5,500. Thus, this analysis assesses the cost of this 5,500-truck stock transitioning to ZETs by 2030; and depicts the investment required to purchase and operate 5,500 ZETs as well as costs of building and maintaining requisite ZET refueling infrastructure. Figure 5 represents how this analysis considers an incremental ZET deployment approach through increasing ZET sales to arrive at the targeted deployment stock of 5,500 ZETs by 2030, a detailed methodology is included in Appendix A.

Figure 5: The total number of ZETs forecasted along the Delhi-Jaipur corridor by 2030



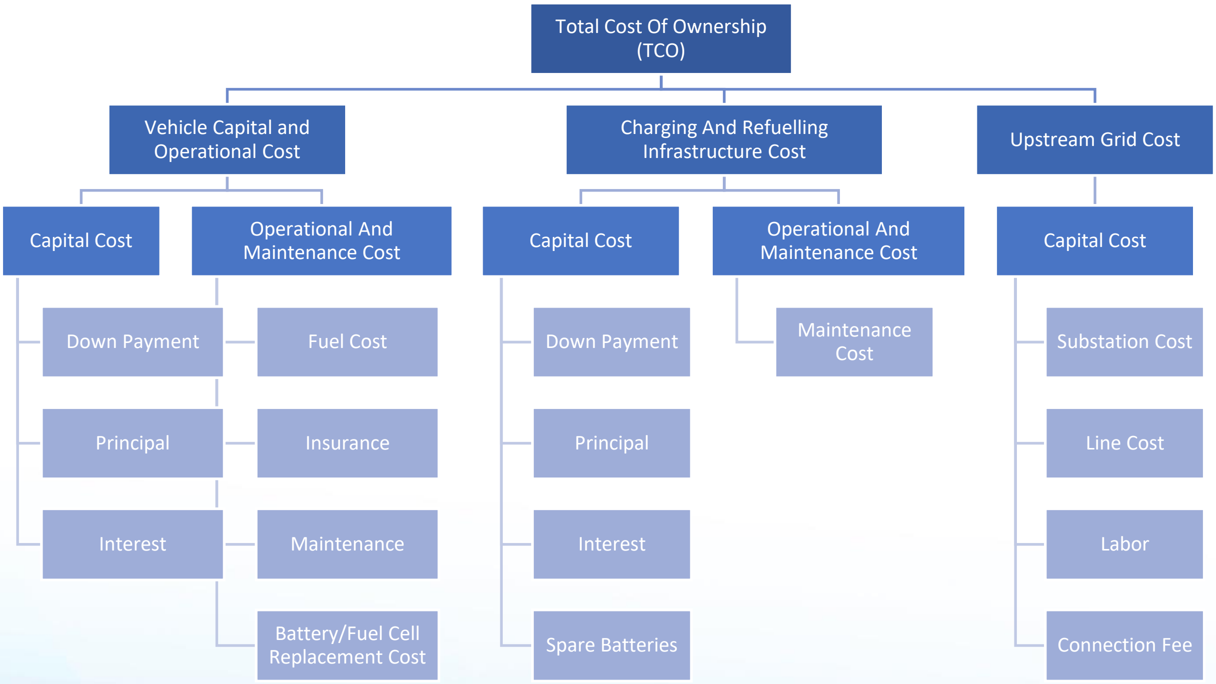
Cost Analysis

Cost considerations are critical for trucking operators and logistics companies when contemplating the transition to ZETs. The total cost of ownership (TCO), the cost to own and operate a vehicle over an operating cycle, serves as a comprehensive assessment to compare the economics of differing technologies and is depicted for heavy-duty trucks (HDTs) and medium-duty trucks (MDTs). The TCO encompasses three primary components:

1. Lifecycle Vehicle Cost: This component encompasses the total cost of purchasing, operating, and maintaining a truck over a ten-year fixed operating cycle.
2. Charging and Refueling Infrastructure Costs: This category includes the hardware, installation, and maintenance expenses for various infrastructure facilities required for different technologies on a per-vehicle basis.
3. Upstream Grid Cost: This specifically refers to the upstream grid upgrade cost associated with battery electric truck technologies. It is important to note that the upstream costs related to hydrogen production, transportation, and storage for hydrogen internal combustion engines (ICE) and fuel cell vehicles are embedded in the fuel cost under the vehicle cost.

The TCO does *not* consider land costs, the operational and maintenance cost of grid upgrades, soft costs, or societal costs; as this analysis focuses on hard costs. For diesel and CNG trucks, the infrastructure to refuel already exists; thus, it is not included in the TCO.

Figure 6: Total cost of ownership breakdown of key cost components



Note: Spare batteries under the charging infrastructure cost apply specifically to battery swapping and include the initial purchase and replacement of spare batteries.

Total Cost of Ownership Results

This section examines the TCO associated with deploying seven distinct ZETs along the Delhi-Jaipur corridor, both in pilot and scaled deployment scenarios. Figures 7 and 8 illustrate the TCO for HDTs and MDTs, respectively, followed by key insights extracted from the analysis.

Figure 7: ZET and diesel truck TCO comparison for HDTs for a pilot (avg. 2025 price) and scaled deployment (avg. 2030 price)

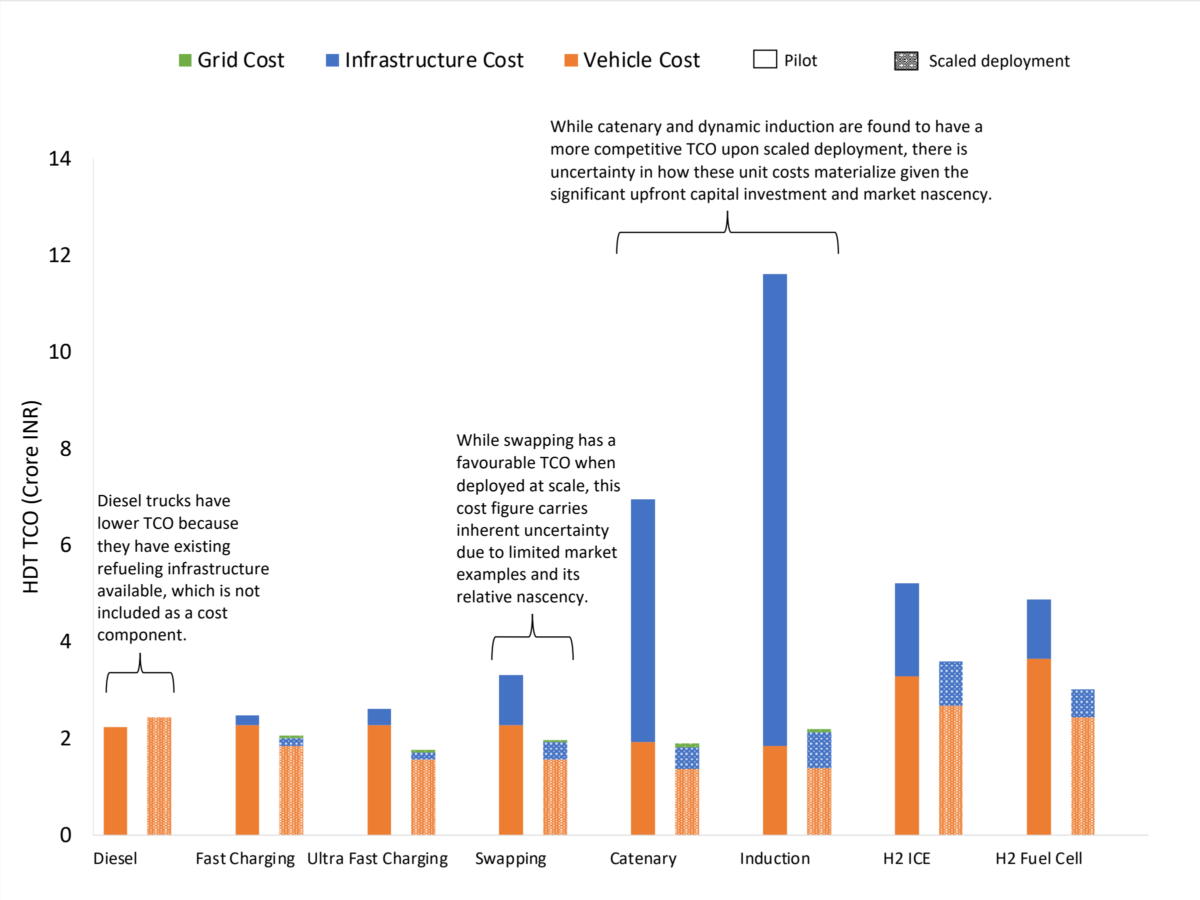
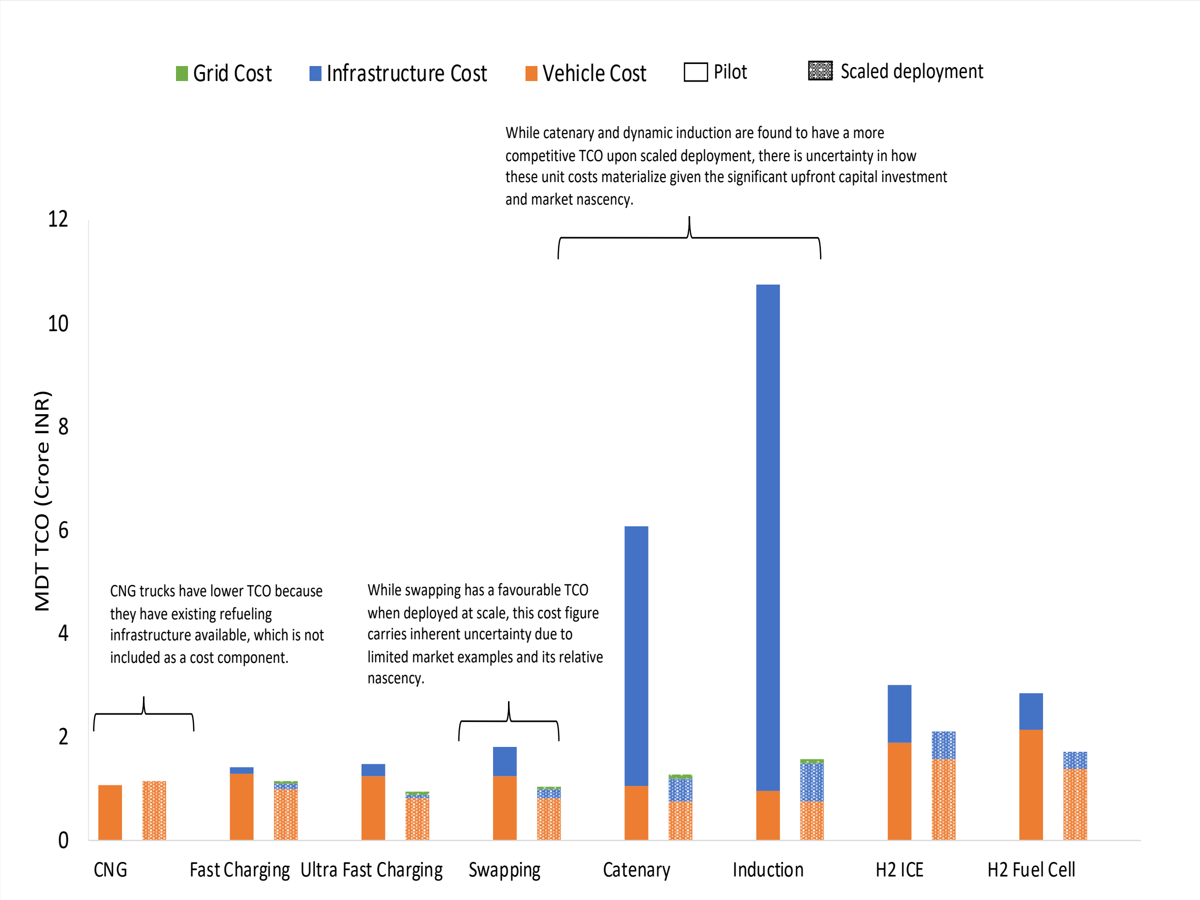


Figure 8: ZET and CNG truck TCO comparison for MDTs for a pilot (avg. 2025 price) and scaled deployment (avg. 2030 price)



While ZET technologies initially exhibit higher costs compared to diesel and CNG during the pilot phase in 2025, the TCO for battery electric trucks becomes more favorable than their Internal Combustion Engine (ICE) counterparts by 2030 due to economies of scale.

In the pilot phase, HDT diesel exhibits an 11% lower TCO than the lowest-cost ZET technology, while CNG MDT at the pilot scale demonstrates a 33% TCO reduction compared to the lowest-cost ZET. This discrepancy arises because diesel and CNG trucks have existing refueling infrastructure, which is not factored into their TCO. Among the modeled ZET technologies at the pilot scale, battery electric trucks (BETs) charged via fast chargers or ultra-fast chargers in both the MDT and HDT use case is the most cost-effective option followed by battery swapping. Catenary and dynamic induction represent charging technologies that will be deployed in segments along the length of the corridor, these systems are not competitively priced at the pilot scale due to the substantial infrastructure investments and the limited number of ZETs deployed during this pilot. Hydrogen ICE and hydrogen fuel cell vehicles exhibit TCOs that are 1.5 – 2.5 times higher than fast charging, ultra-fast charging and swapping BET technologies, primarily due to their high vehicle costs and added infrastructure costs.[3]

As economies of scale improve, HDT BET technologies can achieve a 28% to 15% lower TCO compared to diesel, depending on the infrastructure used during the scaled deployment in 2030. BETs, when charged via ultra-fast chargers (500 kW en-route chargers), offer the lowest TCO among various technologies across both the MDT and HDT use cases. This cost advantage arises from gradual adoption through incremental infrastructure deployment, which provides a cost-effective path to scalability. The cost of catenary and induction technologies also decreases significantly as infrastructure cost per truck lowers with higher utilization rates. Hydrogen trucks remain the most expensive option, primarily due to their high vehicle costs, high cost of green hydrogen and low vehicle efficiency.

In the scaled deployment use case, most of the ZET technologies achieve cost parity at or below that of diesel and CNG vehicles. However, these technologies are at varying degrees of market maturity, which impacts the availability of cost data and overall confidence in cost estimates, particularly for battery swapping, catenary, and dynamic induction. Technology-specific insights are detailed below:

Figure 9: Total cost of ownership key findings by technology

Technology	Key Points
Fast Charging	- Lowest cost at pilot scale - Allows deployment of relatively low-cost charging assets gradually to meet the incremental charging demand
Ultra-Fast Charging	- Lowest cost at the scaled deployment - High-capacity chargers charge HDT in under an hour and MDT in half-hour, allowing multiple daily uses and enabling stakeholders to deploy fewer assets compared to depot fast-charging
Swapping	- Competitive upon scaled deployment with slightly higher infrastructure costs due to spare batteries at swapping stations - Offset by using smaller batteries, reducing vehicle costs
Catenary & Induction	- Not cost-effective at the pilot scale due to high infrastructure capital investment - Cost-effectiveness increases with higher infrastructure utilization in scaled deployment - Enables the use of smaller truck batteries, reducing vehicle costs

[3] Upstream grid upgrade cost is shown as zero in the pilot scenario. Research and stakeholder interviews have shown that there is enough spare power capacity on the grid, and thus, additional grid equipment is not needed for deploying 100 ZETs on the Delhi-Jaipur corridor. In the meantime, it is important to start planning for the grid investment required for scaled deployment from the pilot year onward because the construction of new infrastructure takes years to complete.

Hydrogen Fuel Cells & Hydrogen ICE Trucks	- One of the highest TCOs - H2 ICE: High fuel costs and lower vehicle efficiency are key cost drivers - H2 FCET: High fuel and vehicle purchase costs are the primary cost drivers

To initiate a ZET pilot, both public and private actors must collectively invest between INR 200 to 1,100 crore, depending on the ZET technology chosen. Fleet owners and operators may bear the vehicle costs, while both public stakeholders and private actors could share the infrastructure and upstream grid costs. To scale beyond a pilot and develop the Delhi-Jaipur highway as a flagship ZET corridor, an investment of INR 8.2 to 17.5 thousand crore will be required, once again contingent on the chosen technology. The specific costs of developing a ZET pilot and corridor are illustrated by technology in the figure below. These costs represent the total expenses for deploying 100 ZETs during the pilot phase and 5,500 cumulative ZETs upon scaling up, including the required refueling infrastructure and grid costs.[4]

Figure 10: Cumulative investment required for pilot and scaled deployment from 2025 to 2030

ZET Technology	Investment Pilot in 2025 (Crore INR)	Cumulative Investment for scaled deployment by 2030 (Thousand Crore INR)
Fast Charging	195	9.5
Ultra-Fast Charging	204	8.4
Swapping	257	9.4
Catenary	651	8.2
Induction	1118	9.1
H2 ICE	411	17.5
H2 FCET	387	15.2

Text Box 1: The role of financing for ZET assets and the necessity of the ZET secondary market development

Access to financing will play a crucial role in advancing ZET adoption due to the large amount of investment required for ZET procurement and production. Currently, a ZET's upfront cost is higher than a diesel counterpart's, and very few demand off-takers have the capital to procure a ZET outright. On the supply side, manufacturers, as is often the case in many nascent markets, require initial capital to invest in ZET production facilities. As the market stands today, ZET financing is a higher-risk endeavor than lending to conventional diesel

[4] The total investment cost does not include soft costs, the monetization of risk or the monetization lane closures due to construction

trucks due to several factors: a ZET is a more expensive asset, there are greater operational uncertainties, and there is no established secondary market.

One crucial means to lower the risks of lending to ZETs will be establishing a more stable residual value for used ZETs. Developing a ZET secondary market and securing a stable residual value for used ZETs will play an outsized role in increasing ZET adoption for several reasons. Firstly, the used truck represents the lion's share of annual truck sales in India. For ZETs to replace diesel trucks, used ZETs must derive value in the secondary market. Secondly, establishing a secondary market can give financiers confidence in the liquidation value of ZETs, enabling them to reduce their loss given default. Thirdly, trucks in India today are operated for as long as 20 years and have two, sometimes three or more owners throughout their lives. Given an asset's prolonged life, the secondary market or used truck market is a core component of the sector. Finally, the trucking market is also very disaggregated, with over 75% of the freight market made up of small owner-operators who own fewer than five trucks. This makes the trucking market very cost-conscious.[17] Thus, the initiation of a ZET secondary market is fundamental if ZETs are to be operated by truck owner-operators and truly achieve market penetration.

To initiate ZET market development, financers, OEMs, fleet operators, and policymakers, all have a role to play and must work to derive and converge on a secondary market price for ZETs. Financers look to the secondary market to indicate whether they can lend to an asset class. Lenders want to be able to reduce their loss given default. If they need to repossess a vehicle, having confidence that some value can be retained enables financiers to price their risks. Such assurance is needed to begin mobilizing greater capital flows to ZETs. By developing business models like leasing to support the secondary ZET market and sharing battery state of health data, stakeholders can build market confidence and work to converge on a ZET salvage value. Ultimately, implementing financial tactics aimed at risk reduction and supporting the ZET secondary market can strengthen the lending proposition for ZETs.

The next three sub-sections dive deeper into each component of the TCO, i.e., 1) vehicle cost, 2) refueling infrastructure cost, and 3) upstream grid cost.

Vehicle capital and operational cost breakdown

Methodology: The vehicle cost encompasses the vehicle capital cost (CAPEX), which includes upfront expenses such as down payment, interest, and principal payments, along with operational costs, comprising annual insurance fees, battery replacement, maintenance, and truck refueling or charging costs. Detailed assumptions for calculating these vehicle costs are provided in Appendix B.

The vehicle cost was determined by calculating the combined cost of the truck (including the chassis and power electronics) and the battery. Battery costs were adjusted based on the required size for the Delhi-Jaipur duty cycle, considering refueling time and infrastructure placement for each technology. For catenary and Dynamic Induction trucks, an additional equipment cost for installing a pantograph or Dynamic Induction coils was included. Vehicle costs include interest, principal, and down payment, assuming a five-year loan at a 15% interest rate. Operational costs depend on truck efficiency; total distance traveled, and electricity expenses for charging. Battery replacement occurred between years 7 and 9 based on charging cycles and the Delhi-Jaipur duty cycle. Total vehicle costs were modeled over a 10-year cycle, with each cost element discounted to 2025 at a 15% rate.

Key cost components for hydrogen trucks include upfront pricing, fuel, maintenance, and fuel cell replacement (for FCETs). Upfront pricing is calculated using a bottom-up approach considering the truck and powertrain balance. H2 ICE trucks have an engine and H2 storage tank, while H2 FCETs feature a fuel cell, battery, and storage tank. Fuel costs for H2 trucks are based on delivered hydrogen prices, vehicle efficiency, and total kilometers traveled. Vehicle costs were modeled over 10 years, with each component discounted to 2025 at a 15% rate.

The vehicle cost of a diesel truck serves as the baseline for comparison for HDT truck costs, and diesel truck costs were based on the market average price for a 31-tonne truck. Similarly, the cost of a CNG truck was used for comparative purposes in the MDT vehicle class, the CNG truck cost was derived from the market average price for a 12-tonne truck. The primary cost element for both diesel and CNG trucks is fuel, determined by the duty cycle and annual average prices. Diesel and CNG trucks have favorable lending rates due to a mature market with established practices and a clear secondary market, with a 9% interest rate applied over a 5-year loan period for diesel trucks.

Results and insights:
Figures 11 and 12 highlight the vehicle costs for HDTs and MDTs for the pilot in 2025 and scaled deployment in 2030.

Figure 11: HDT vehicle (capital and operational) cost comparison under the pilot (2025) and scaled deployment (2030) over lifetime

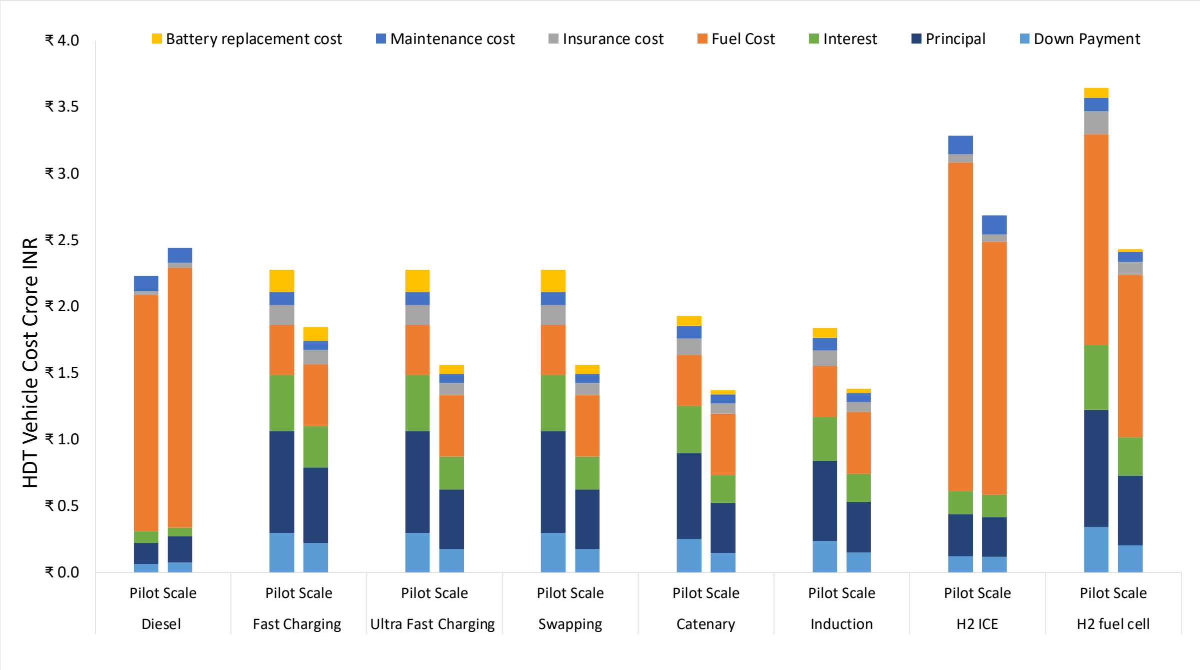
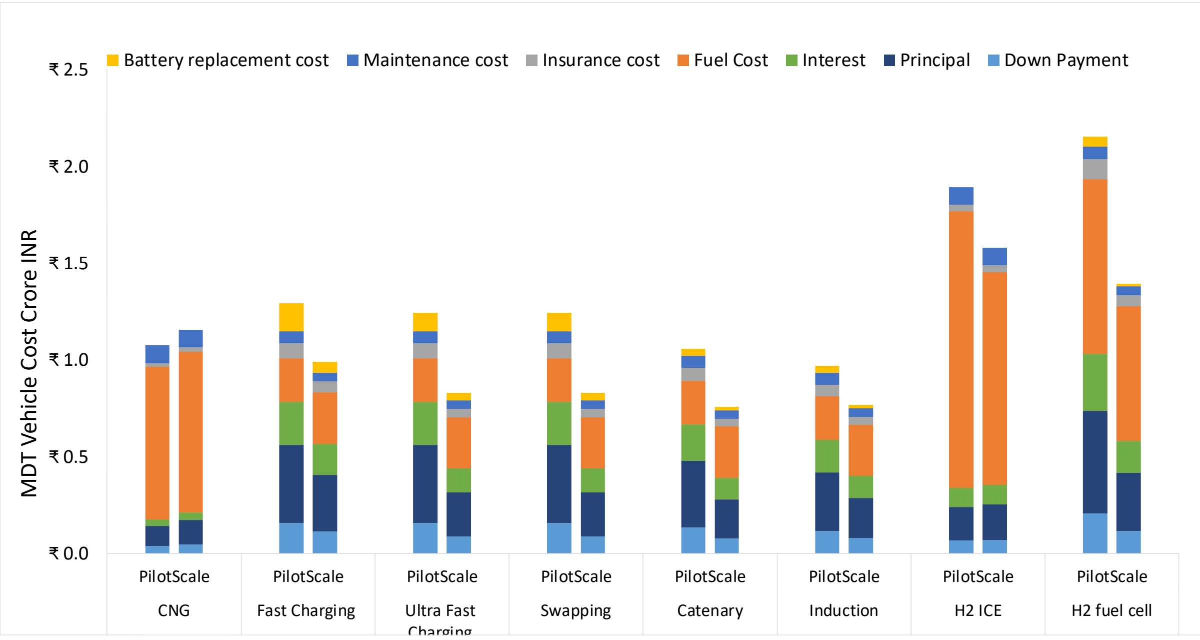


Figure 12: MDT vehicle (capital and operational) comparison under the pilot (2025) and scaled deployment (2030) over lifetime



The results indicate that even in the pilot scenario, the costs of owning and operating HDT BET vehicles are approaching parity with diesel trucks. This is primarily attributed to the significantly lower fuel expenses associated with BETs compared to diesel trucks. For example, the fuel cost for a heavy-duty battery electric truck is only a quarter of that for its diesel counterpart, assuming the average EV tariff in the pilot scenario and then projecting a 20% increase in this tariff to match the average industrial tariff by 2030. Upon scaled deployment by 2030, BETs' operational and capital costs combined are lower than diesel trucks. The vehicle cost of a diesel vehicle experiences only marginal changes in the two scenarios, as it is already a mature technology produced at economies of scale. At the pilot scale, MDT CNG vehicles have lower TCO due to their relatively affordable purchase price and lower fuel costs compared to diesel. However, with the economies of scale by 2030, the capex of the BET MDTs is lower than the CNG counterpart.

In both trucking segments (MDT and HDT), the cost differences among the five BET technologies are primarily determined by their vehicle battery sizes. Fuel and maintenance costs remain consistent across all BET technologies due to consistent annual vehicle kilometers traveled and comparable efficiency levels resulting from loading. Fast-charging trucks have the largest battery size, which contributes to higher vehicle upfront costs, and insurance costs. Battery size for swappable and ultra-fast charging trucks is 33% lower than other fast charging BETs on account of faster charging times. This reduction in battery size will lead to lower vehicle cost in the scaled deployment by 2030. Dynamic induction and catenary trucks incur additional costs for installed pantographs or dynamic induction coils. However, this hardware enables en-route charging and reduces battery size, leading to significant capital expenditure (CAPEX) reductions, see Appendix-B for further details of how vehicle costs were modeled and derived.

Hydrogen internal combustion engines (H2 ICE) and Hydrogen fuel cell trucks (H2 FCET) have the highest vehicle costs in both pilot and scaled scenarios. For H2 ICE, the primary cost driver is fuel, accounting for 75% of total expenses during the pilot phase due to the high cost of green hydrogen and relatively lower vehicle efficiency. Fuel cost for H2 ICE decreases with the scaled deployment by 2030 given the expected decline in green hydrogen prices. H2 FCET initially has lower fuel costs than H2 ICE and diesel for HDTs and higher fuel costs than CNG for MDTs in the pilot scenario. By the scaled deployment in 2030, as green hydrogen prices drop, the fuel costs for H2 FCET become lower than diesel and CNG trucks. Despite this, high upfront purchase costs prevent hydrogen FCET vehicle costs from reaching parity with ICE vehicles. H2 FCET has the highest initial purchase cost due to the expensive fuel cell system in the pilot scenario. With scale, the fuel cell system cost is expected to decrease significantly, leading to a 44% reduction in vehicle CAPEX for MDTs and a 41% reduction for HDTs compared to the pilot use case.

Refueling infrastructure cost breakdown

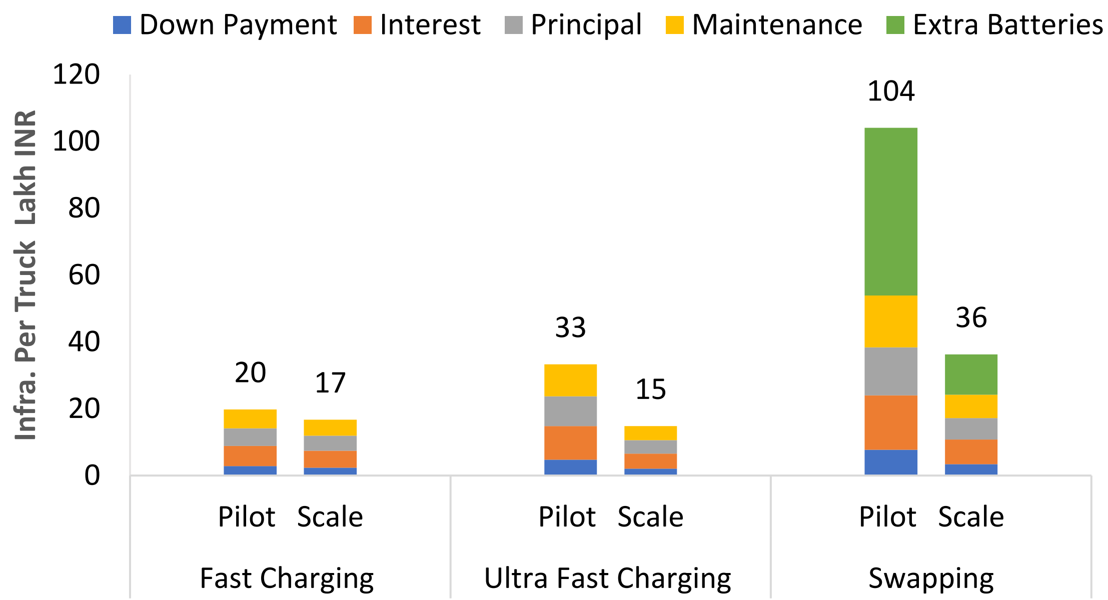
Methodology: Infrastructure costs were modeled to optimize for both operability and cost. To ensure smooth operations, several factors needed consideration. Firstly, there should be sufficient refueling infrastructure to accommodate truck travel. Second, it should be strategically spaced along the corridor to facilitate mobility between Delhi and Jaipur. However, cost-effectiveness is also a crucial factor, and the infrastructure assets should be well-utilized to justify the investment. To strike a balance between these two parameters, a modeling approach was developed to determine the appropriate locations and sizes for the infrastructure. Further details are described below:

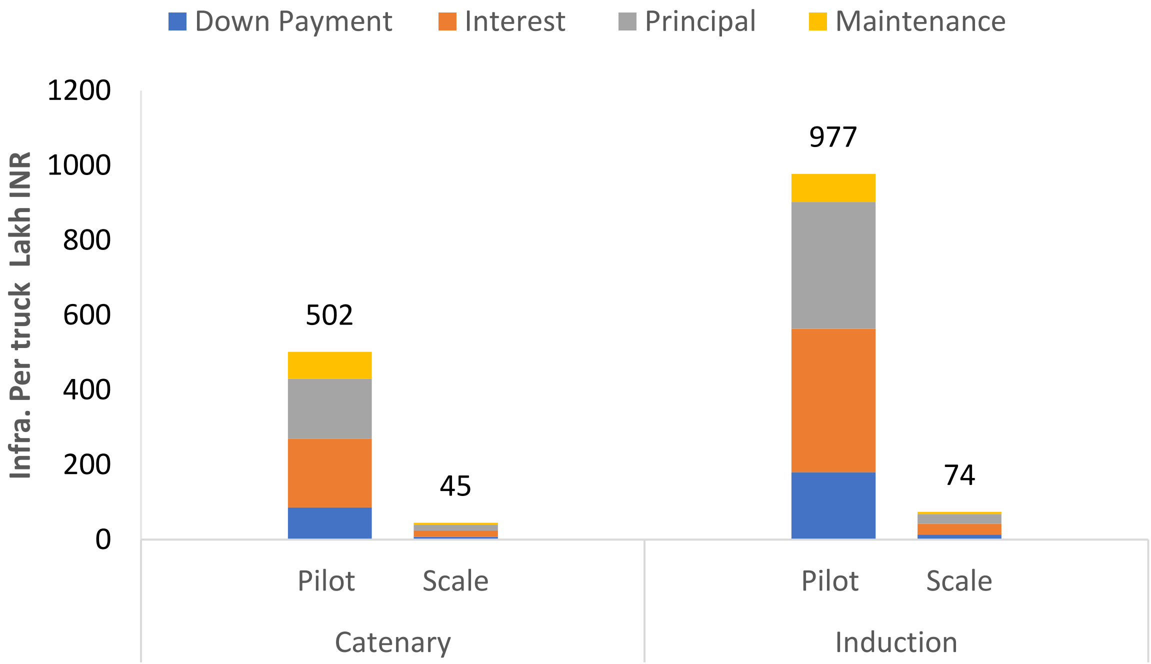
- Fast Charging: 100 kW fast chargers at depots would require a charging time of nearly 5-6 hours for HDTs and 3-4 hours for MDTs. These chargers would commonly be utilized overnight or between truck operating shifts.
- Ultra-Fast Charging: The pilot scenario uses current technology available in India, with a maximum power capacity of 240 kW chargers capable of charging a vehicle in 1-3 hours. At scaled deployment, a 500-kW charger is utilized, facilitating charging times in under an hour for HDTs and MDTs as the battery in these vehicles can be downsized (see Appendix-B for details).
- Battery Swapping: Battery stations are assumed to be established at hubs along the Delhi-Jaipur corridor to facilitate en-route battery swapping. Each station is equipped with spare batteries to meet the demand for truck swapping. The truck-to-spare battery ratio decreases from 0.4 in 2025 to 0.3 in 2030 for HDTs, and from 0.3 in 2025 to 0.2 in 2030 for MDTs.
- Catenary: In the pilot scenario, three 10 km roadway stretches were assumed to be equipped with overhead wires. By scaled deployment in 2030, a more extensive network of wires is considered, covering six segments along the Delhi-Jaipur corridor, spanning 80 km in either direction. Further details are available in Appendix-C.
- Dynamic Induction: This analysis assumes that dynamic induction charging is developed for en-route truck charging, similar to the description provided for catenary charging. However, in this case, coils are installed beneath the highway. Additional details can be found in Appendix-C.
- Hydrogen Refueling: Hydrogen refueling stations are placed at each end of the corridor and along one central hub between Delhi and Jaipur based on a derived station capacity at pilot and scaled deployment.

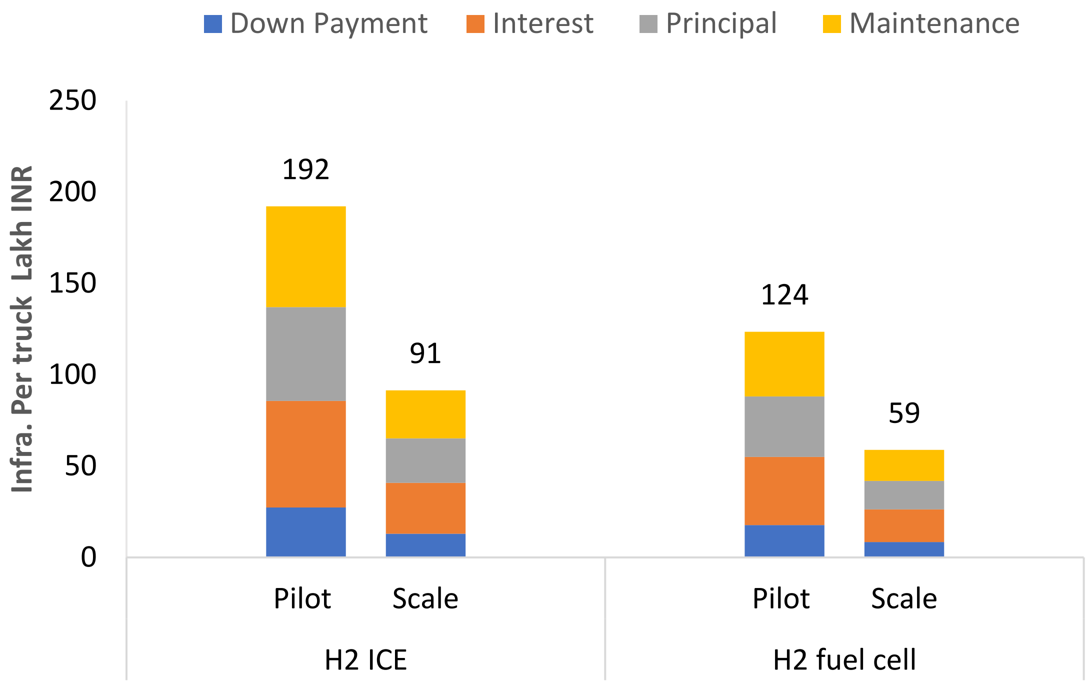
Total capital costs encompass hardware and installation expenses, represented in the graph as down payment, interest, and principal. Maintenance costs were calculated based on the specific technology and amortized over a 15-year operating cycle.

Results and insights: The results presented below highlight the infrastructure costs for providing refueling in the pilot scenario in 2025 and upon scaled deployment in 2030. These infrastructure costs are categorized based on vehicle type. Figure 13 illustrates HDT infrastructure costs, which are higher due to the greater refueling demand, while Figure 14 depicts MDT infrastructure costs.

Figure 13: HDT Infrastructure costs expressed in Lakh per vehicle for pilot and scaled deployment

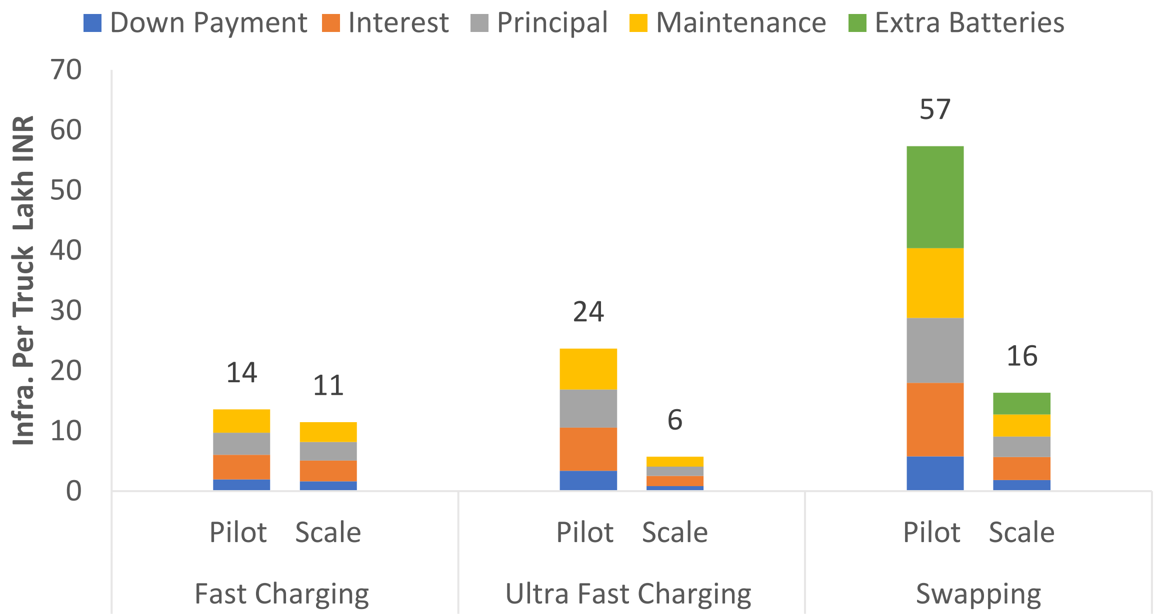


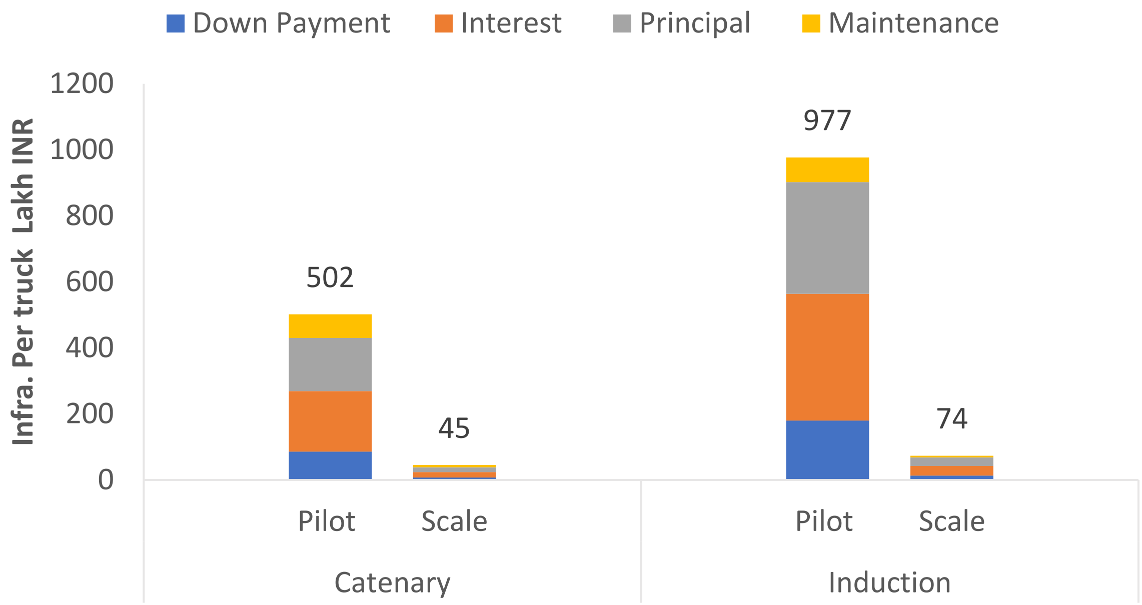


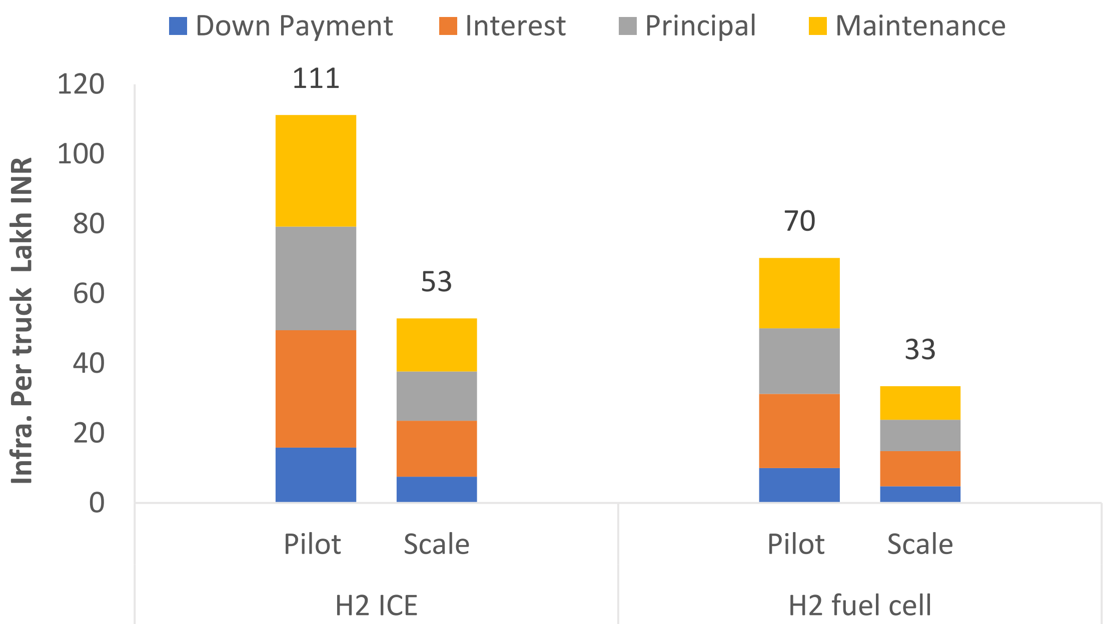


Note: The graphs are shown separately due to the differing y-axis required to accurately depict the cost of these technologies. Spare batteries refer to the spare batteries in battery swapping stations. It includes the initial cost to purchase spare batteries and the battery replacement cost when spare batteries retire.

Figure 14: MDT Infrastructure costs expressed in Lakh per vehicle for pilot and scaled deployment







Note: The graphs are shown separately on account of the differing y-axis required to accurately depict these technologies' costs. Spare batteries refer to the spare batteries in battery swapping stations. It includes the initial cost to purchase spare batteries and the battery replacement cost when spare batteries retire.

Fast charging at depots and ultra-fast charging are cost-effective at the pilot scale because chargers can be deployed incrementally to meet truck charging demand. However, based on derived asset utilization and charging placement ultra-fast charging en-route is proven to be more cost-effective upon scaled deployment, as fewer chargers can meet the charging demand, details provided in Appendix-C.

Battery swapping is cost-effective in both pilot and scaled deployment scenarios, with the primary cost driver being the spare batteries stations must maintain. In the pilot scenario, these extra batteries are close to 50% of the infrastructure cost, whereas in the scaled deployment, they range from 22% to 33% of the total cost, depending on whether they are designed for MDTs or HDTs.

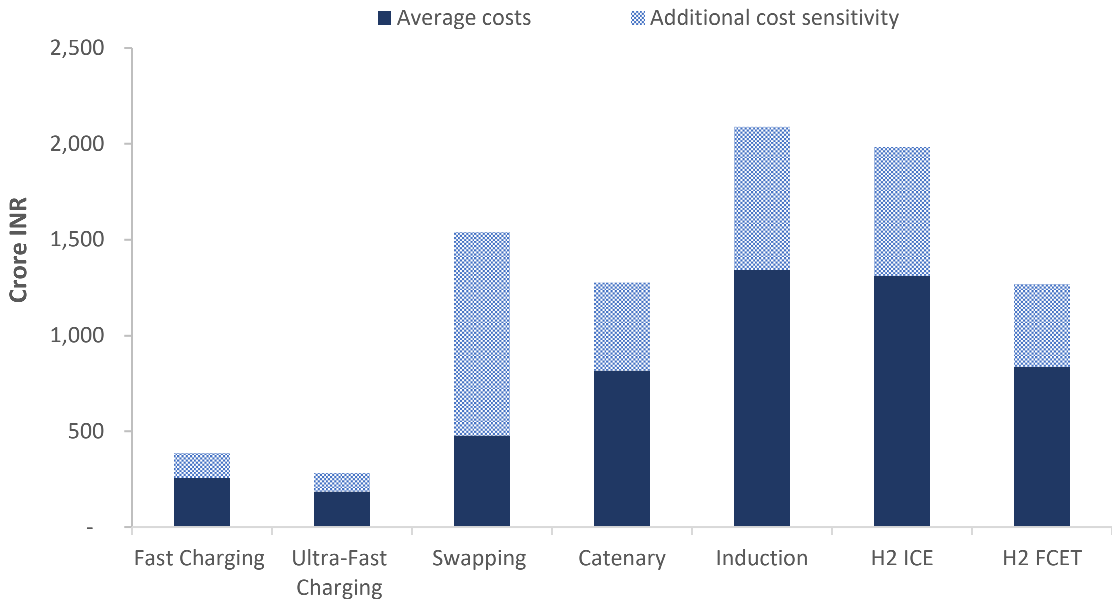
The costs associated with catenary and dynamic induction infrastructure are notably high in the pilot scenario. This is primarily due to the necessity of constructing extensive stretches of overhead wires or inductive coils, which are not cost-effective when catering to just 100 trucks at the pilot scale, given the substantial expenses involved in hardware and installation. However, both become far more cost-effective upon scaled deployment due to the high utilization rate, as the same infrastructure can support additional vehicles without requiring further investment.

Hydrogen refueling stations are expensive to deploy during the pilot stage due to their lower capacity and lower utilization. However, with scaled deployment, high-capacity stations can reduce infrastructure costs as more trucks enter the corridor. Additionally, infrastructure costs for H2 FCETs are lower than for H2 ICE vehicles in both scenarios due to their higher efficiency. This results in fewer refueling stations needed for FCETs to serve the same number of trucks, thus reducing infrastructure costs.

Refueling infrastructure cost uncertainty*:* Refueling infrastructure costs for ZETs are uncertain due to the emerging nature of ZET infrastructure deployment and varying technology maturity levels. These cost variations become more pronounced when considering scaled deployment since no single technology has been deployed at a significant scale to date. [18]

Figure 15 illustrates the sensitivity in cost when adjusting various components of the infrastructure cost, including hardware, installation, maintenance, and number of spare batteries. The dark blue bars represent the average total infrastructure cost upon scaled deployment, while the dotted bars indicate additional cost sensitivity. More details on how cost sensitivity was determined can be found in Appendix C.

Figure 15: Infrastructure investment cost uncertainty at scaled deployment



Battery swapping and induction technologies exhibit the highest level of capital cost uncertainty. For swapping technology, batteries account for half of the total infrastructure cost in the pilot scenario and over half in the scaled deployment. There is inherent uncertainty regarding the required spare batteries at each station to adequately meet swapping demand, leading to a high variance in infrastructure costs. Regarding induction technology, the market data available to date does not provide a clear understanding of how dynamic induction coil hardware and installation costs will decrease per kilometer. Similarly, there is considerable uncertainty surrounding catenary per unit costs for similar reasons. In addition, hydrogen infrastructure costs exhibit significant variance due to the high unit cost of infrastructure equipment and maintenance costs. Lastly, fast charging and ultra-fast charging also present high variability in the infrastructure cost, due to similar uncertainties related to per-unit charging station hardware costs and maintenance costs.

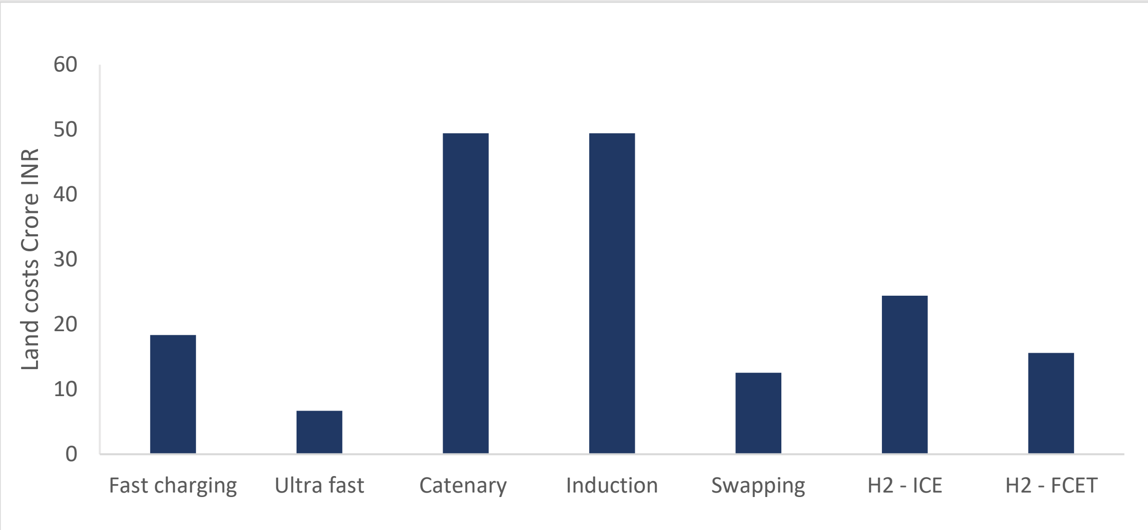
Text Box 2: Land Costs

Land costs are crucial when evaluating the economic viability of a specific ZET infrastructure solution. Proper placement of infrastructure assets is critical for seamless ZET refueling. Therefore, strategically identifying refueling hubs and land parcels for infrastructure development is crucial for ZET's operational effectiveness. Land costs, including those for refueling and parking, are indirect expenses associated with all types of truck movements and are often not factored into TCO. In this analysis, these costs have been independently modeled and assessed to ascertain the feasibility of various technology pathways.

The cost of land for developing the necessary infrastructure along the Delhi-Jaipur corridor was calculated by estimating the amount of land required for charging/refueling facilities, with consideration given to the number of charging or refueling assets needed and the number of refueling and recharging hubs. The average land price was ascertained through interviews. Next, the total area required per the differing ZET technology was derived.[5] For fast and ultra-fast charging, the land was sized based on the number of chargers required at a hub (per Appendix-C). For swapping, the land area was based on the number of swapping stations at a hub. The total area for catenary and induction systems was determined by the distance covered by the catenary wires or dynamic induction coils along the corridor. In the case of hydrogen refueling, the mechanics are somewhat akin to CNG refueling, and the land required was derived based on land required for CNG stations in India; specific details on the quantity and cost of land are detailed in Appendix-C.

The total land cost was then calculated based on the size of the land parcels by technology and the average square meter land price. Figure 14 depicts the net present value of purchasing land, with consideration given to the fact that actors would borrow to purchase the land, and the valuation of land over time is also included in the calculation, as detailed in Appendix-C. These costs are calculated for the scaled deployment of 5,500 ZETs by 2030.

Figure 16: Land Costs along the Delhi-Jaipur corridor across the differing technologies under scaled deployment



Based on the modeled results, catenary and induction systems incur the highest land costs due to the requirement of spanning coils or wires over an 80km distance in each direction.

[5] The area derived was solely for infrastructure operations and should be taken as the minimum amount of land required to functionally operate a given refueling solution. The land parcel size utilized to estimate costs does not include access points for maintenance, or land utilized during construction activities. Lastly, land required for request grid infrastructure was not accounted for.

H2 ICE follows with the next highest land costs due to space requirement for hydrogen storage, multi-stage high-pressure compressors and dispensers. Ultra-fast charging and swapping have lower land costs because they require smaller land parcels and offer relatively fast charging times.

While these results illustrate land costs for different technologies, it's important to note that land purchase agreements and the value trucking operators derive from using the land for charging and refueling may vary significantly. For example, fast charging includes the inherent value of parking trucks overnight for charging, as trucks not operating around the clock need land for parking, whether rented or purchased. Therefore, the cost and benefit of parking are already factored into the charging land cost, potentially inflating it. Another important consideration is that catenary and induction systems must be installed within the highway, which is owned by the government. Modeling land costs for this infrastructure type is inherently more complex, as it may require developing agreements or public-private partnerships to establish such infrastructure.

Upstream grid cost breakdown

Methodology: The final component of the TCO of ZETs is the upstream infrastructure cost, i.e., grid upgrade cost for BET charging. For hydrogen trucks, the production and transportation costs of hydrogen are already integrated into the fuel cost; therefore, they are included as part of the vehicle's operating costs. For further details, please refer to Appendix D.

Based on the derived truck charging demand, the grid upgrade costs were calculated using the four-step approach described below:

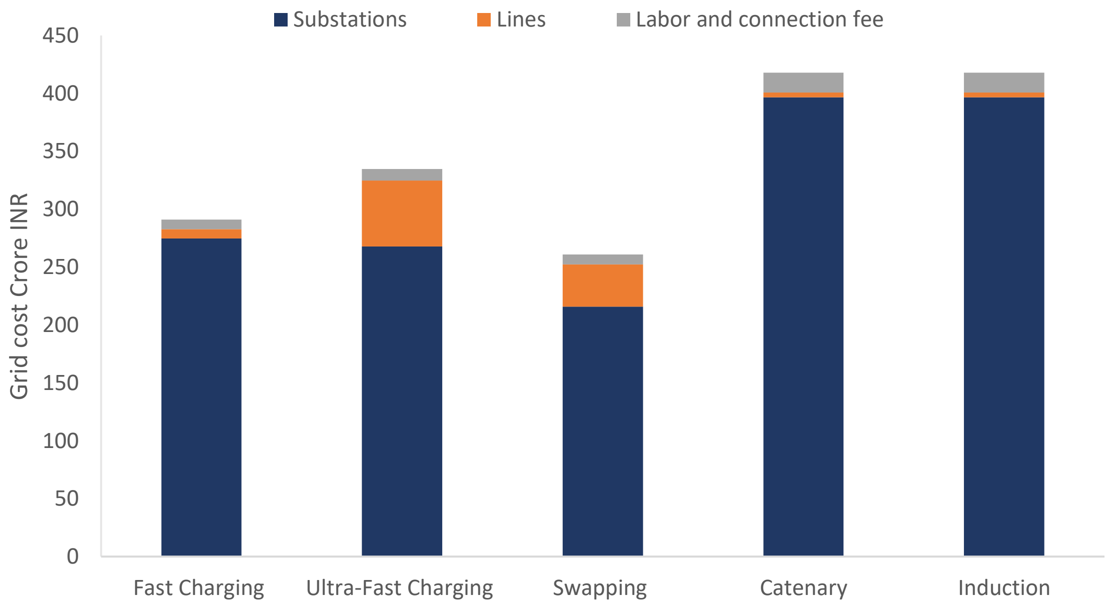
1. *Evaluate Existing Grid Capacity:* The first step involved assessing the available power capacity on the transmission and distribution network along the corridor. It was evaluated that there are seven major substations next to the Delhi-Jaipur corridor, and the transmission lines have around 100 MW of spare capacity. In the pilot scenario, the existing lines and substations can provide enough grid capacity for truck charging. In the scaled adoption scenario, new substations need to be constructed to support truck charging demand.
2. *Determine Peak Loads at Stations:* The second step involved calculating the peak load at each charging station based on truck charging patterns. The peak load for ultra-fast charging, catenary, and dynamic induction were quite similar, as these technologies were considered en-route charging options. It was assumed that the peak load would occur to accommodate the morning peak traffic and subsequent coincident charging events. The peak load remained constant during operational hours for battery

swapping since all spare batteries were charged simultaneously. In the case of fast charging, the peak event was expected during a coincident evening charging session when a significant portion of trucks needed a full charge. More detailed information on how peak loads were derived can be found in Appendix D.

3. *Assessing the Electrical Equipment Needed to Meet Peak Demand:* At the distribution level, the current spare capacity is adequate for the pilot scale. However, upon scaled deployment adequate distributional capacity to charge 5,500 trucks is not available. To meet this scaled demand, new electrical infrastructure will be required, including additional distribution lines, substations, and transformers to step the voltages down from the transmission level to the charger. The quantity of added distribution lines was determined based on the extension required to connect a charging station to the nearest substation. The specific substation equipment required depends on the chosen infrastructure technology and the voltage that such equipment can receive.
4. *Deriving the Costs of Requisite Electrical Equipment:* The costs of the required equipment, labor, and per-unit costs are derived from the distribution company's cost data books.

Results and insights: The total grid upgrade costs for the scaled deployment by 2030 are shown in Figure 17; the costs represent the hardware and labor cost during construction.

Figure 17: Grid upgrade cost of five BET technologies at scaled deployment



Among all technologies, the most significant cost category is substation costs. The costs associated with lines, labor, and connection fees are relatively smaller when compared to the substantial substation expenses. The locations of existing substations and their available spare capacities play a critical role in determining whether a new substation is necessary to meet the demand for truck charging. Additionally, strategically placing charging hubs near existing substations can help reduce the costs associated with installing new distribution lines and labor.

Ultra-fast charging has a slightly higher grid upgrade cost than fast charging, mainly driven by its higher line cost. In the scaled adoption phase, the 500kW high power charger to shorten charging time to around an hour requires higher voltage lines at the charger level. The 33kV line it uses is more expensive than the fast charging's 11kV line. The substation costs of the two technologies are not significantly different, driven by the fact that fast charging at depots places a nearly equivalent peak load on the grid compared to ultra-fast charging on the road.

Similar peak loads are driven by the charger number, power and charging times of these two technologies. While fast - charging technology requires only 100kW chargers, it necessitates more chargers to meet overnight charging demand. Consequently, a significant coincident peak charging event is anticipated to occur during the overnight period, typically between 11 p.m. and 4 a.m., in order to cater to the morning surge in truck trips departing from the greater Delhi area. Ultra-fast charging can be completed in just about one hour; thus, the coincident peak is mitigated as fewer 500kW chargers are required per hub.

Battery swapping technology offers the lowest cost due to its relatively lower peak load. This is mainly attributed to its ability to replace a battery in a matter of minutes, allowing for gradual charging of batteries over extended periods or during off-peak hours, effectively managing the peak load. Catenary and induction systems are anticipated to encounter relatively high peak events because, to ensure sufficient charging for trucks, they will need to draw power from the catenary or dynamic induction segments located near Neemrana or Delhi during peak traffic events. For more detailed information, please refer to the additional details provided in Appendix D, which includes information on the size of electrical equipment utilized and the associated cost of upgrading these systems.

Overall, the primary driver of grid costs is the derived peak loads, as these directly influence the investment required in substations. To gain a more detailed understanding of charging peaks, traffic patterns, and opportunities for managing truck charging loads, further real-world evidence is essential before grid upgrades can be effectively planned and executed.

It is important to note that the cost and planning horizon for facilitating truck charging are significant. Therefore, it is imperative for fleet operators, DISCOMS, and PowerGrid to initiate planning for grid upgrade costs as early as 2025 at the initiation of ZET deployment. This proactive approach is crucial because resource planning and the construction of grid equipment are processes that span several years. By estimating peak load requirements for scaled deployment and commencing the grid upgrade process as early as possible, both time and costs can be saved in the long run.

It is also important to recognise that soft costs related to permitting, project coordination, and construction delays can indeed have a real impact on the overall project cost. These soft costs are highly specific to each project and, therefore, are not explicitly quantified in this analysis. Furthermore, delays in the shipment of materials and disruptions in procurement supply chains can affect both vehicle and infrastructure costs. When considering grid upgrade costs, the planning and coordination processes with DISCOMS and transmission companies are additional soft costs that should be taken into account. To minimise these soft costs, stakeholders should proactively plan for the deployment of ZET technologies and increase their awareness of the various potential soft costs that may arise during the implementation phase. By doing so, they can better manage and mitigate these factors to ensure the successful and cost-effective deployment of ZET technologies.

Performance, technology, and market assessment

When fleets consider transitioning to ZETs, they seek products that match or outperform traditional diesel trucks. In assessing the operation and performance of ZETs, operational fleets must consider several critical factors. These factors include vehicle operations such as payload capacity, range, overall efficiency, and the ability to rapidly charge or refuel a ZET. Also, technology readiness plays a vital role, encompassing the technology's maturity and associated risks related to technology lock-in and aftermarket support. This section highlights these considerations' advantages, constraints, and risks and outlines the applicable use cases for various ZET technologies. Figure 18 provides a summary of the performance, technology, and market assessment factors.

Figure 18: Evaluation of ZET technologies across performance, technology, and market assessment criteria

Legend
Highest level of risk, posing significant challenges or potential drawbacks
Moderate level of risk, presenting some challenges or uncertainties.
Lowest level of risk, offering favorable advantages or having fewer drawbacks.

Consideration	Fast charging	Ultra-Fast Charging	Swapping	Catenary	Induction	H2 ICE	H2 FCET
Performance							
Payload	X	X	X	X	X	X	X
Refueling	X	X	X	X	X	X	X
Technology							
Technology lock-in	X	X	X	X	X	X	X
Technology and commercial maturity	X	X	X	X	X	X	X
Market							
Driver training, installation and aftermarket support	X	X	X	X	X	X	X

Performance considerations

Fleet operators consider two primary performance criteria when contemplating the switch to ZETs: payload capacity, which refers to the vehicle's load-carrying capacity, and range, the ability to cover the required daily distances without experiencing range anxiety.

Payload:
Payload capacity is determined by subtracting the truck's kerb weight from its gross vehicle weight rating (GVWR). The kerb weight of the truck varies depending on the specific

powertrain type and size associated with each technology choice. Consequently, the kerb weight and payload differ depending on the chosen technology.

Fast charging at depots necessitates the use of larger battery packs to meet daily operational needs when traveling between a truck's origin and destination pair. Trucks with swappable batteries can have smaller batteries because of the advantage of quick refueling and availability of wide access to swapping stations, as can catenary and dynamic induction trucks when en-route charging infrastructure is available. While battery downsizing can be advantageous from a cost standpoint, it has implications on the range, as a reduced battery size will limit range, and without substantive en-route refueling infrastructure this can present range anxiety challenges

Payload capacities vary, with BET fixed battery trucks having the lowest, swappable battery trucks having higher, and catenary/induction-based trucks having the highest payload capacity amongst BET trucks. In contrast, hydrogen-based trucks can offer payloads comparable to diesel trucks and superior to BET trucks. This is due to the higher energy density of hydrogen, which allows for smaller onboard hydrogen weight to meet daily operational needs, thereby increasing payloads. However, hydrogen tanks take up a lot of volumetric space (depending on any restrictions on truck length), and in cases where a shipment is volume-constrained (like E-Commerce), hydrogen trucks are not the most suitable option.

Refueling considerations:

Given that all powertrains are right-sized to operate on the 300km Delhi-Jaipur corridor, refueling times and widespread availability become an important factor for developing operator confidence in ZETs and their ability to perform equivalent to ICE trucks.

The charging or refueling characteristics of BETs and H2-based trucks vary significantly. Fast Charging at depots leads to longer charging times of 4-6 hours, adding to the downtime and necessitating operators to opt for larger batteries to satisfy daily operations. However, a network with ultra-fast chargers can reduce charging times to 1 hour, mitigating this concern. Swappable batteries offer quicker swaps in 3-5 minutes, enhancing operational confidence if a widespread network of swapping stations is available. On the other hand, electrical roadway systems such as catenary and dynamic induction technologies for BET trucks enable continuous charging while in motion, offering the least charging downtime. In contrast, H2-based trucks stand out as they can refuel at H2 stations in just 10-15 minutes, similar to diesel trucks, providing operations comparable to traditional diesel vehicles.

Preserving battery state of health:

For battery electric truck technologies specifically, the preservation of the battery's state of health is a key consideration. The battery represents over 50% of the truck's cost and the preservation and longevity of a battery have a significant impact on the ability of the vehicle to meet its range requirements, it will also have a driving influence over the salvage value of a truck. Once a battery reaches a depleted (~80%) state of health it needs to be replaced if it is expected to meet the same duty cycle. The speed at which batteries are recharged as well as the power they are charged at is a risk to the preservation of the battery's state of health. Differing charging technologies therefore present potential advantages and uncertainties pertaining to the preservation of the battery's state of health.[19]

With ultra-fast and fast charging, there is a need for continuous monitoring of battery charging since high-powered charging can potentially have a detrimental effect on battery health. Battery swapping stations have the potential to effectively manage charging over extended durations. This slower, prolonged charging approach can contribute to maintaining battery health, potentially leading to longer battery life spans and reduced replacement costs. While this advantage currently cannot be quantified due to the lack of sufficient data, it presents the possibility of tangible benefits in the future. For dynamic induction systems, the ability to control the transfer of current at specific times and avoid transferring current when the battery is fully charged is a crucial factor for preserving a vehicle's battery health. In the case of catenary charging, how operators handle the charging process and the pantograph system's capability to monitor current flow will play a significant role in ensuring the battery's health. Lastly, it is important to note that the impact of various charging technologies on battery health has not been definitively established, as these technologies have not yet been widely deployed at scale.

Technology assessment

A holistic assessment of trade-offs and an evaluation of market trends are crucial when making decisions about deploying and investing in ZET technology. This includes factors such as technological maturity to meet operating requirements and technology lock-in i.e., the system's inability to harness emerging technological innovations.

Technology maturity:
Different ZET technologies are at varying stages of technological and commercial maturity. Policymakers and business decision-makers need to take this factor into account when choosing a particular technology or supporting infrastructure development.

Figure 19: Technology maturity for vehicles

BETs	BETs are in a more mature stage of development, with hundreds of BET models available globally and a few in India operating in closed-loop operations. Some OEMs in India are currently prototyping and testing BETs.[20]

H2 trucks	H2-based trucks are in a less mature stage compared to BETs when it comes to model availability and commercial operations. The H2 ICE technology is still in the prototyping and testing phase.[21] For H2 FCETs, pilots are happening around the globe, with a majority of them taking place in the USA.[22] One pilot project has been announced for port operations in India.[23]

Figure 20: Technology maturity for infrastructure

Fast Charging at depots and ultra-fast Charging	Fast chargers are being used for overnight charging for buses in major cities like Pune.[24] Buses have a similar battery size as trucks making them a prime example supporting the feasibility of employing fast charging solutions at depots for BETs.
Ultra-Fast Charging	The largest charges deployed in India to date have been 240kw chargers for various e-bus operations across Mumbai.[25] However, 500kw chargers are needed to facilitate truck charging within approximately an hour. Therefore, investments in the manufacturing and development of such chargers are essential for the advancement of this technology.
Catenary	From a technological perspective, catenary systems have been used for other transit modes to provide traction power to buses and rail networks. However, catenary technology would be relatively untested in the context of trucking applications, and using power delivered to charge the batteries and deliver traction power. While companies in Germany are working on pilot-scale catenary truck projects, the commercial viability of these networks is yet to be established.[26]
Induction	While induction technology is not a recent innovation, only a handful of small-scale dynamic induction systems exist for vehicle and bus applications globally. As these systems have not yet reached commercial-scale implementation, concerns regarding the use of proprietary technology could inflate costs during scaling.
Swapping	Swapping technology for trucks is more mature and has been deployed at a significant scale in China. In India, proof of concept has been developed through battery swapping via robotic arms for electric buses, however, its applicability and use in other heavier vehicles hasn’t reached maturity yet.
H2 refueling infrastructure	Technologically, hydrogen refueling stations are relatively mature because standard equipment like compressors, storage units, and dispensers are also deployed in petrol pumps. There were about 636 hydrogen refueling stations across the globe by the end of 2022, mainly in North America, Europe, Japan, and Korea. However, most of the stations are designed for use by light-duty vehicles, while large-capacity stations for heavy vehicles are yet to be commercialized.[27] Currently, two refueling stations for fuel cell buses are being planned in Delhi and Leh.[28] However, more investment is required in high-capacity stations for heavier vehicles to enable commercial maturity and lower costs.

Technology lock-in:

Assessing the risks associated with deploying and investing in rapidly evolving technologies is a critical step for decision-makers. This evaluation helps in avoiding potential pitfalls, such as deploying technology that may quickly become outdated or incurring substantial sunk costs.

Figure 21: Technology lock-in for trucks

BETs	Battery electric trucking technologies are evolving rapidly with advancements in battery chemistry. Historically, nickel manganese cobalt batteries dominated due to their high energy density, but alternatives like lithium-iron-phosphate batteries, which are cheaper to produce, are gaining traction. Emerging technologies like solid-state batteries with double the energy density could disrupt the market. Investing in a battery that eventually is obsolete is a moderate risk, however, our modeling shows that battery replacement is required every 7-9 years thus over the course of a truck's operational life, it would have an opportunity to replace its battery with more advanced chemistry, resulting in a low lock-in effect.
H2 Trucks	Transitioning to H2 ICE trucks can be swiftly managed by OEMs since they can be produced on existing assembly lines, leveraging the familiarity of manufacturers with diesel engines. However, as the NOx reduction requirements become stricter, stakeholders could prefer other zero-emission technologies that don’t emit any tailpipe pollutants. H2 FCET requires substantial new investments as they represent a different technology with limited overlap with diesel engines. This necessitates a shift in production methods and the creation of new production lines, posing an investment risk if demand for other clean technologies outpaces the adoption of hydrogen.

Figure 22: Technology lock-in for infrastructure

Fast Charging at depots and ultra-fast Charging	Chargers can be deployed to meet market demand incrementally, allowing users to adopt the latest technology with low sunk costs. The installation of level 2 chargers is becoming widespread, especially in urban areas, demonstrating its viability as an infrastructure solution. However, there is a risk where ultra-fast charging options can make fast charging solutions obsolete on account of customer preference for faster charging times and technology improvements leading to minimal impact on battery health
Swapping	Due to the need for additional batteries, swapping could create cost redundancies. If other technologies offer operational benefits like faster recharging times, the added cost may not be justified, potentially leading to obsolescence risks. Moreover, if ultra-fast charging can compete with swapping in terms of refueling time, swapping further faces the risk of obsolescence.
Catenary & Dynamic Induction	Developing a catenary network or dynamic induction network takes several years, given the complex and lengthy design, engineering, and construction components. During this extended development period, it is possible that alternative technologies may advance, potentially diminishing the practicality of

	catenary and dynamic induction systems. Investing in catenary or induction infrastructure systems presents substantive risk as it requires a significant investment that may not be fully utilized. Additionally, if BET batteries are downsized following en-route charging ability trucks will be constrained to operating along a sole corridor with limited range beyond this application.
H2 refueling infrastructure	Creating dedicated hydrogen transport pipelines demands a substantial initial investment, as natural gas pipelines are unsuitable due to hydrogen's corrosive nature. Similarly, establishing a comprehensive network of refueling stations carries significant upfront costs. Given that H2-based technologies are still nascent, there is an inherent risk of overspending on infrastructure that could become obsolete.

Market assessment

Market development is a critical factor when switching to a new ZET technology. This encompasses various elements, including the acquisition of technical knowledge, driver training, infrastructure installation support, and ongoing servicing and maintenance support for the assets necessary to facilitate ZET trucking operations.

Figure 23: Market support for vehicles

BETs	Battery electric vehicles are being adopted at an accelerated rate in India's light-duty and bus segments. As their adoption grows, the aftermarket sales of spare parts and service offerings would likely ramp up and mature. Given that the powertrains for BETs would be similar to other segments, BETs can take advantage of India's growing aftermarket support and services, and shared supply chains for EVs.
H2 trucks	After-market and servicing support for H2 ICE will resemble diesel and CNG trucks, given the similarities in the powertrains. Moreover, there are synergies with shared supply chains for hydrogen production as the same hydrogen would be used for various other industrial use cases like steel, ammonia, etc. However, servicing of FCETs, particularly for fuel cells and hydrogen tanks, will necessitate new capabilities and upskilling, given that the market is non-existent.

Figure 24: Market support for infrastructure

Fast Charging at depots and ultra-fast Charging	• Driver skilling: EV charging operations entail relatively easy tasks requiring drivers to physically connect trucks to chargers, hence no major upskilling is required. • Installation: Establishing charging stations involves trenching and cabling at the charging hub, leading to construction and installation expenses. This will require an increase in the qualified labor force. With India’s rapidly growing economy, those kinds of skills will be in demand by multiple sectors.

	• Aftermarket support: To ensure efficient charging deployment and access, a robust network of service technicians is essential. The trucking industry can leverage existing workforce networks developed for bus and passenger vehicle plug-in charging to support the development of infrastructure and to adequately maintain charging assets.
Swapping	• Driver skilling: The mechanical process of replacing a battery would be relatively seamless for drivers. • Installation: Battery swapping stations would require the development of mechanical or robotic swapping stations with space for charging multiple truck batteries. • Aftermarket support: Battery swapping is gaining traction in India's two and three-wheeler sectors and the skills training and existing technical knowledge can transfer to support truck swapping and behavioral familiarity. However, service offerings for maintaining robotic swapping facilities will be essential.
Catenary	• Driver skilling: Drivers need to ensure continuous contact between the pantograph and overhead wires for power transfer. Monitoring the pantograph's engagement and disconnection from the wires is essential to minimize maintenance issues. • Installation: Establishing catenary infrastructure demands significant planning and engineering expenses, including pole installation along the corridor and the placement of crash pads. • Aftermarket support: Many business providers are already servicing and mass-producing key equipment such as poles and wires for electric bus and rail applications. Leveraging the electric rail workforce can help generate robust aftermarket support.
Dynamic Induction	• Driver skilling: Effective use of Dynamic Induction relies on charging when directly under the charging coils, typically within 20-30 cm. This can present challenges if trucks are not driving explicitly in a dedicated lane. • Installation: Installing Dynamic Induction involves road cutting, but trenching for coils only needs to be around 10cm below road grade. Thus, installation can often be timed with road resurfacing. • Aftermarket support: Servicing the power transfer mechanics for both the road system and vehicles requires specialized technical knowledge. Since only a few firms offer this technology, it may lead to an overreliance on a limited number of operators.
Hydrogen refueling station	• Driver skilling: Refueling stations would operate similarly to existing CNG stations, so trucking operators would not need to change their behaviors. • Installation: Setting up H2 refueling stations requires installing storage units, high-pressure compressors and dispensers which entail substantial costs.

	• Aftermarket support: The market for essential components of refueling stations, such as compressors, storage units, and dispensers, is well-established, as they are used in CNG stations and other industries. Some upskilling may be necessary due to the corrosive nature of hydrogen and requirement of multi-stage compression, potentially altering the approach to servicing key equipment.

Case Studies

The following section presents a series of case studies illustrating the deployment of each technology in trucking applications. These case studies offer a real-world perspective on the dissemination of ZET solutions and showcase the key actors involved and their current efforts. The goal is to provide insights for policymakers and decision-makers on how to implement various ZET technologies tailored to specific trucking use cases.

Fast Charging at depots in the United States of America

Project Specifics: Phase-wise fleet electrification approach with a focus on depot fast charging.

The state of the market: Multiple charging deployment hubs have been developed across the US and Europe. Many actors have found depot charging to be an applicable solution especially when trucks return to a base and operate relatively fixed routes.

Case Study: *OK Produce*, a wholesaler specializing in fresh produce based in Fresno, US, is currently in the process of implementing ZETs to meet their freight transportation requirements. In this endeavor, OK Produce has forged partnerships with leading automakers such as Daimler, Volvo, and Orange EV to procure ZETs. Additionally, they have teamed up with ABB for the deployment of depot fast chargers and BP Pulse to optimize management.

To efficiently support its daily operations, the company has devised a phased approach for investing in ZETs and the necessary depot charging infrastructure. Phase 1 of this plan involves the deployment of 13 ZETs, each of which will be charged via fast chargers capable of providing 60kW of optimally designed power for each truck.[29] The second phase of their fleet electrification journey from early 2024 will include leveraging partnerships with renewable energy and charging station providers to supply 14 additional fast chargers that will serve an additional 27 ZETs for daily operations. Moreover, their charge management software ensures that some of their depot charging needs are met through the 12,000 solar panels that they have deployed since the launch of their sustainability program.[30]

The OK Produce depot charging infrastructure offers a clear roadmap for sustainable fleet energy solutions. Their charging system underscores the importance of adaptive chargers that adjust to varying energy demands, promoting operational efficiency. Additionally, their phased approach suggests that a tiered rollout can mitigate risks, allowing for iterative testing and refinement. Collectively, OK Produce's strategies present a concise blueprint for an effective depot charging model suitable for wider emulation.

Source: RunOnLess

Ultra-fast Charging of Zero-Emission Trucks at WattEV's Port of Long Beach Facility

Project Specification: 13 dual-cord CCS 360KW chargers; 5MW capacity for concurrent charging of 26 trucks at up to 360KW each

The state of the market: Several high-capacity en-route charging hubs are planned in California to facilitate seamless ZET Mobility. Similar projects are also underway in Europe to support the ZET transition.

Case study: The Port of Long Beach is one of the busiest ports in the western hemisphere, handling nearly 10 million ton-equivalent units a year and accounting for nearly 20% of loaded containers moving through all US ports.[31][32] Given its sheer scale, transitioning to electric trucks can have an outsized environmental and economic impact. The Port has begun to make ambitious strides in electrifying goods movement by opening an ultra-fast charging hub capable of charging trucks in 1-2 hours. The hub, developed by WattEV, is equipped with 26 360KW chargers manufactured by Charge America, the site can draw up to 5MW of power.[33]

While it is a public charging station, the new charging hub also serves WattEV's growing fleet of electric trucks operating on its Truck-as-a-Service platform, hauling freight to and from the combined ports of Long Beach and Los Angeles. In addition to its CCS system, which is the current charging standard for heavy-duty electric trucks, there are plans for the introduction of the Megawatt Charging System to further enhance charging speeds, allowing pass-through trucks to be charged in as little as 20 minutes, which will be close to the time drivers take for stops.[34]

This initiative is part of a larger vision to establish a charging freight corridor connecting major freight routes in the region. The facility was constructed in 14 months at an estimated cost of $5-6 million (INR 41-50 crore), funded through partnerships with companies and nonprofits including Calstart, Southern California Edison, and the Harbor Community Benefit Foundation.[35] With evolving charging standards and the expected introduction of trucks with higher charging capacities, the depot's infrastructure may see further developments in the future to bolster California's mission of accelerating the transition to all-electric transportation in the heavy-duty trucking industry.

Source: WattEV

Battery Swapping Corridor in China

Project Specification: 420-kilometer battery swapping corridor with four swapping stations in Southeast China; Each station has eight spare batteries.

The state of the market: Battery-swappable trucks have been deployed primarily in short, closed-loop applications globally. China is currently the only geography in which battery swapping is provided along a longer regional corridor span for trucking.

Case study: China is scaling the adoption of ZETs in the country by strategically investing in battery-swapping corridors. The government has rolled out various policies, including national-level targets, subsidies, and battery standardization policies, to scale ZET adoption.[36] In this pursuit, multinational conglomerates have taken the lead in implementing battery-swapping infrastructure along crucial trucking routes.

One example is the electrification of a segment of the Shenhai Expressway in China, co-developed by the Chinese battery manufacturer CATL and Fujian Expressway Group. This battery swapping ZET corridor costs around 47.5 million CNY (INR 54 crore INR) and was officially launched on August 24, 2023.[37] Covering approximately 420 kilometers of this route, which links the southeastern cities of Ningde and Xiamen, specialized truck swapping stations have been established. These stations, each equipped with eight spare batteries, efficiently exchange depleted onboard truck batteries with fully charged replacements, completing the entire process in five minutes. Truck operators traversing this stretch of highway now have the convenience of swapping their batteries when they approach low charge levels at the dedicated swapping stations situated along the corridor. Presently, 20 ZETs are operating on the Ningde-Xiamen battery swapping corridor. It is expected that this number will increase to 300 in 2024, along with the construction of a new swapping station. [38] Interviews with truck drivers on this battery swapping corridor show that on average, one ZET can save 30,000 CNY (INR3.4 Lakh) to 50,000 CNY (INR 5.7 Lakh) of operating cost on an annual basis compared to its diesel counterpart. [39]

In addition to the Ningde-Xiamen corridor, two other battery-swapping corridors for battery-swappable trucks have been announced in China. These projects represent a key component of a broader initiative led by the Chinese government to promote the electrification of heavy-duty vehicles.

Source: CnEVPost

Catenary Highway Segment in Germany

Project Specification: A 13km catenary highway segment supporting battery electric truck mobility.

The state of the market: The deployment of catenary infrastructure exclusively for battery electric truck use is still in its nascent phase of development. At present, only a handful of pilot projects have been executed globally, with notable pilots occurring in Germany, Italy, France, Norway, and Sweden. However, these systems have been implemented over relatively short distances, primarily designed to assess the feasibility and practicality of this technology within the realm of trucking.

Case study: Germany is at the forefront of pioneering catenary infrastructure for trucking through the development of extensive field trials aimed at evaluating and implementing this innovative technology to support electric trucking. The German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, in collaboration with Siemens, a leading e-highway technology provider, and Scania, an electric truck manufacturer, have developed a motorway featuring an overhead catenary system located outside the Frankfurt Airport.[40]

This project began with the creation of a 5km e-highway segment in 2019, and in 2022, it was extended by an additional 7 km. [41]The test trucks used in these trials are equipped with both batteries and pantographs. Pantographs connect with the overhead cables, which are positively and negatively charged and suspended from numerous masts positioned along the innermost lanes of the highway. While Scania, a trucking manufacturer, agreed to manufacture paragraphs for trucks to operate along the corridor of the German government-funded infrastructure development; the total cost to develop overhead cables was estimated at 2-2.5 million euros (INR 17.5-21.9 crore) per kilometer.[42]

Since initial compilation, five battery-electric heavy-duty trucks have been operational on the corridor, allowing stakeholders to closely monitor energy efficiency and truck performance. In the initial phases of the pilot, researchers have observed that trucks can maintain peak speeds of 90km/h while still being able to connect and disconnect their pantographs.

Source: Scania

Dynamic Induction test tack in Gotland Sweden

Project Details: A 1.65km Dynamic induction pilot supporting electric truck mobility.

The state of the market: Dynamic induction deployment projects are still in their early stages and tend to be on a smaller scale. These limited-scale pilot projects have been predominantly conducted in Norway and Sweden and have been instrumental in testing the feasibility of inductively charging electric trucks while they are in motion. While there have been other induction pilots for electric buses and other EVs, the number of projects specifically focused on trucking has been relatively low.

Case study: Sweden aims to reach net-zero emissions across the road freight sector by 2030. To meet this goal, Sweden has employed a variety of charging technologies, including electric road systems where trucks are charged via Dynamic Induction coils embedded beneath the roadway.

An exemplary pilot project showcasing this technology is the Smartroad Gotland project, established in Gotland, Sweden. This initiative was launched by Trafikverket, the Swedish Transport Administration, and was led by the Smart Road Gotland consortium in collaboration with Electron, an electric roadway technology company. In December 2020, the project conducted its initial tests using a fully electric 40-ton truck along a 1.65km stretch of Dynamic Induction roadway, connecting the city center to the airport.[43] The reported budget for this demonstration was estimated at around USD 12.5 million (INR 103 crore) to install the underground coils.[44]During these tests, vehicles were able to reach speeds of up to 80 km/h and received an average power supply of 70 kW from the electrified roadway.

Source: Electron, a photo of the induction coils that transfer power to trucks, these are then covered with asphalt, and lie ~10cm under the roadway grade.

Hydrogen refueling at the port of Los Angeles

Specifics: 10 T680 FCEVs (Fuel Cell Electric Vehicles) using three hydrogen refueling stations

The state of the market: Hydrogen fueling technology for trucks is relatively nascent. With research and development rapidly progressing, there are a handful of announced hydrogen trucking pilots. However, most of these pilots are in a preliminary development phase.

Case study: The "Shore to Store" project was established in the Port of Los Angeles to implement real-world usage of Class 8 hydrogen-fueled trucks in port drayage operations. Initiated in 2019, this large-scale demonstration project was a collaboration between Toyota, Kenworth, and Shell. The project cost $82.5 million (INR 0.7 thousand crore); funding was raised via both public and private sources with $41.4 million (INR 342 crore) in contributions from project partners, and a $41.1 million (INR 340 crore) grant from the California Air Resources Board (CARB). [45]

The pilot culminated in the development of 10 specialized T680 FCETs by Toyota-Kenworth, intending to showcase the potential of Class 8 fuel cell-electric trucks as a zero-emission alternative to traditional diesel-powered counterparts. The 10 trucks for this project were operated by customers, including, among others, Toyota Logistics Services, Total Transportation Services, Inc. and Southern Counties Express. To support these trucks, Shell constructed and managed two high-capacity hydrogen refueling stations in Wilmington and Ontario to ensure easy fueling access for the fleet.[46]

The results of the pilot demonstrated that FCETs could perform equivalently to diesel trucks in terms of range for this example and power during daily operations. As part of the pilot, the FCEVs exhibited a 300-mile range with a carrying capacity of 82,000 lbs. A notable advantage of hydrogen fuel cell technology was the quick refueling time, typically between 15 to 20 minutes. This efficiency allowed for multiple operational shifts in a single day, enabling the trucks to cover distances ranging from 400 to 500 miles (640 – 800 km) without downtime. In addition to operational benefits, replacing one diesel truck with an FCET resulted in an annual reduction of 75 tonnes of CO_2 emissions.[47]

While the "Shore to Store" project underscored the technical feasibility of FCETs in real-world scenarios, their economic viability has remained a challenge. It is estimated that an FCET in early-stage commercial production in 2025 in the US will cost approximately USD 400,000[48] (INR 3.2 crore) compared to the current cost of USD 150,000[49] (INR 1.2 crore) for a diesel truck in the US. The average cost for a hydrogen refueling station in the US is around USD 2 million (approx. INR 16 crore), with an average capacity of 1,240 kg of hydrogen per day.[50]

Source: Toyota

Complementing ZET Technologies

Considering the emerging nature of the ZET market, the ongoing advancements in research and development, and the diverse requirements of the trucking industry, one ZET technology may not capture the entire trucking market. However, the various ZET technologies described can complement each other effectively. To achieve this synergy, two key strategies can be implemented:

1. Optimal selection and matching of technologies by use case: By carefully selecting and matching ZET technologies based on specific use cases, both operators and infrastructure providers will be better equipped to meet the varying operational needs of freight transportation.
2. Promotion of interoperability between trucks and batteries: By ensuring interoperability among trucks and their respective battery systems, different ZET technologies can be adopted in tandem.

This section highlights how the ZET technologies presented can collectively provide the road freight ecosystem with a series of solutions to fully transition away from diesel vehicle use.

Matching ZETs with ideal use cases

The technologies presented in this report have differing cost, operational, technological, and market advantages, and each ZET technology is well-suited for particular use cases. Figure 25 presents a detailed overview of ideal use cases, explaining where and why specific ZET applications may be more advantageous for a given technology.

Figure 25: Ideal use cases for ZET technologies along the Delhi – Jaipur corridor

Fast charging at the depot	• Fleets with overnight depots or trucks that can return to base at the end of a shift. • Routes with set origin and ending destinations and readily available downtime for charging. • For example, finished industrial goods are typically volume-constrained and return to their bases.
Ultra-Fast Charging (en-route)	• Highly traveled trucking segments where infrastructure can have high utilization and there is enough upstream power availability. • Trucks with an operating schedule allow en-route 1-2 hours of charging time. • For example, frequent e-commerce containerized trips between Delhi and Jaipur often do not utilize a truck's entire payload capacity.
Catenary & Dynamic Induction	• Fleets deployed along short, fixed, closed-loop corridors near infrastructure require minimal charging downtime. • For example, the shipping of construction aggregates along NH48.

Swapping	• Fleets conduct frequent trips under closed-loop systems and have limited downtime for charging. • For example, auto parts and e-commerce movement with frequent round trips are best suited for this technology.
H2 trucks	• Fleets traveling high daily distances with limited downtime or a highly constrained operating schedule. • Weight-constrained applications such as heavy bulk goods. • For example, the shipment of construction aggregates, cement, and blue metal.

Interoperable Trucks

Differing ZET technologies will likely not emerge in silos. Therefore, infrastructure and trucks can be designed in such a way as to enable multiple charging or refueling options. Below is a series of examples of how ZET infrastructure solutions can be deployed to facilitate more seamless charging and refueling:

1) *En-route ultra-fast charging + Fast charging at depots:* En-route ultra-fast charging + Fast charging at depots: Ultra-fast Charging and fast Charging at depots are well positioned to be co-developed along the Delhi-Jaipur corridor. These technologies can serve to complement each other as depot charging can enable operators to conveniently charge overnight, while access to en-route ultra-fast charging can enable actors to downsize their battery, while still being assured that a given truck can meet requisite range requirements.

2) *Battery charging +* swapping: Developing ZETs to accommodate both plug-in charging and swapping can enable operators to have access to a broader range of charging options and match these solutions per a given duty cycle. However, swapping enables battery downsizing, thus fixed charging would meet requisite charging needs for relatively short-range trips. Such trucks are already available in China's ZET market, enabling operators to use both charging mechanisms based on operational performance needs. Developing these solutions tangentially can help operators place swapping stations where they are most needed, increasing utilization. Potentially facilitating overnight charging and midday swapping to facilitate low truck uptime.

3) *Battery charging + Catenary or Dynamic Induction:* Catenary trucks can occasionally travel further outside their fixed routes to alternative destinations if they can charge via a plug-in charger. By charging via fast or ultra-fast chargers, the highway need not be fully equipped with overhead wires, reducing infrastructure costs while enabling some en-route charging.

Ultimately, ZET technologies can be complementary, however rapid declines in costs or rapid gains in capabilities of any technology could lead to the potential obsolescence of other technologies. One technology may gain significant market share due to the rapid decline in costs or the rapid gains in capabilities. When a technology becomes more cost-effective and offers significant improvements in its capabilities, it will become attractive to consumers and businesses. This attractiveness can lead to increased adoption and market share.

Explore Opportunities to Utilize Interoperable Batteries

Another potential means to promote wider use of a range of ZET technologies is by exploring opportunities to incorporate interoperable batteries. Currently, battery packs in vehicles are not standardized, which means that batteries are incompatible across various vehicle segments and model types. Interoperability involves using the same battery in different ZET models and entails establishing standards for pack size, connections, and battery voltages to enable interoperability at the battery pack level. One opportunity to address standardization is through the establishment of interchangeable battery guidelines between different ZET models and even electric buses. The five primary ways in which interoperability could potentially support ZET market development along the Delhi-Jaipur corridor and more broadly are as follows:

- Economies of scale: Interoperability can enable aggregation, broadening the market of suitable and interchangeable battery applications across the trucking and bus segment.
- Reduced cost: Interoperability could enable inventory and spare costs to come down and would also work to streamline maintenance operations as personnel could be trained to fix, swap, and replace standardized batteries.
- Safety and reliability: By standardizing the battery, clear provisions could be developed to accommodate technological evolution, ensuring engineering standards are met better to promote battery operability, durability, and safety.
- Reduce financing risk: Interoperable batteries and standardization could be a means to also reduce the residual value risk of ZETs, as market actors would be better assured that batteries could be resold and repurposed for another mobility application, and provide actors with greater confidence that their used batteries can generate real value in the secondary market.
- Quality assurance: Ensuring a degree of standardization for battery pack and charging safety can create greater market confidence and further support quality control and performance. Such can be developed in a manner that seeks to assure quality to consumers, while at the same time will not infringe upon innovations in battery cell development. Thus, balancing product quality and progressive innovation.

Given these advantages, stakeholders can consider implementing battery interoperability guidance. At the same time, they should carefully manage and monitor the truck's battery management and charging systems to ensure the long-term health of the batteries is adequately supported.

Roadmap

The following solution pathways can be leveraged to support the deployment of a ZET pilot along the Delhi-Jaipur corridor and subsequently scale ZET adoption.

Ideation Phase: The corridor is announced, technologies are determined, and key industry players are convened and consulted.

- *Formally announce a pilot for ZETs along the Delhi-Jaipur corridor:* The government can publicly announce the Delhi-Jaipur ZET corridor as a lighthouse corridor for trucking electrification and call for public and private actors to strategize how collective resources can be pooled to deploy ZETs and the infrastructure needed to support an initial pilot.
- *Identify first movers*: Convene early moving industry players, such as forward-thinking fleets and manufacturers with a business interest in scaling ZET production. Work with these actors to deliberate on favorable ZET use cases and the subsequent vehicle characteristics that can meet duty-cycle requirements.
- *Identify the ZET technology (or technologies) suitable for deployment*: Based on the detailed research presented in the report and stakeholder priorities, identify one or multiple ZET technologies that can be deployed in the Delhi-Jaipur corridor.
- *Create a task force to oversee project implementation*: Establish working groups among public and industry participants to gain buy-in for the project and understand locations where infrastructure may be most needed. Based on stakeholder feedback, the task force can develop project milestones with clear objectives.

Planning Phase: The desired infrastructure and grid upgrades are strategized, and investments are channeled.

- *Strategically plan infrastructure deployment*: Infrastructure should be planned strategically to optimize the cost and ZET operability. A phased approach, concentrating investment in Delhi and Neemrana—a key industrial cluster along the Delhi-Jaipur corridor—represents an effective strategy for further concentrating infrastructure investment to facilitate ZET deployment. Charging hubs can be established near highways or requisite grid infrastructure, near distribution systems with spare capacity. Hydrogen refueling can be developed in locations with a high concentration of truck traffic to ensure high refueling utilization rates.
- *Channel investment*: Identify how public and private actors can strategically allocate project risk and financial liability to facilitate financing for the Delhi-Jaipur pilot. Align

how various stakeholders can support ZET production, deployment, and infrastructure development.

- *Design incentives*: The government can create policy incentives such as upfront cost subsidies or tax exemptions to reduce the cost of zero-emission trucks. Public land can also be leased to build charging stations and requisite truck infrastructure between Delhi and Jaipur. For catenary and dynamic induction this could be land subsidies in the form of land use permits to develop infrastructure within the right of way of the highway.
- *Ensure stakeholder coordination*: Foster effective communication and collaboration among all relevant stakeholders, including government bodies, industry players, DISCOMS, and local departments, to ensure alignment of goals and smooth project execution during the planning phase.
- *Develop and train personnel*: Identify the workforce development requirements to guarantee the technical expertise for planning and executing the ZET deployment strategy. Ensure ample qualified electrical personnel for charger installation and maintenance, and train trucking operators to operate ZETs proficiently.

Pilot Phase: The first 100 ZETs are deployed.

- *Open a tender*: A tender can be released to receive bids for the development of charging or refueling infrastructure in Delhi and Jaipur. The tender should encompass infrastructure equipment and the requisite upstream upgrades required to deploy hydrogen refueling or charging at a specific site.
- *Deploy ZETs and infrastructure*: Public and private stakeholders should work in tandem to get the first 100 ZETs in operation. A substantial portion of ZET traffic between Delhi and Jaipur is concentrated along the segment connecting Delhi to the industrial hub Neemrana, creating an ideal location for initial pilot infrastructure. This can enhance asset utilization and generate higher returns on infrastructure investments.
- *Document learnings*: Document the techno-economic parameters and ZET performance. Share operational insights and circulate information on cost-effectiveness and ZET performance to facilitate broader market development.

Scaling phase: 5,500 ZETs will be deployed on the corridor by 2030.

- *Scale ZET production and infrastructure deployment*: Engagement with domestic OEMs is required to understand existing bottlenecks in scaling ZET production to ensure a wider range of models can be produced and sold in India to meet a wider variety of trucking demands.

- *Develop strategies to mobilize finance*: Financial strategies are needed to mobilize investment for funding ZET manufacturing, demand offtake, and infrastructure development. OEMs, fleet operators, financial institutions, and the government can play a role in instituting risk management strategies to increase ZET finance.

- *Scale infrastructure deployment:* There is a need to engage with DISCOMS, transmission companies, and other key energy providers to develop long-term infrastructure planning strategies for truck charging and to initiate the necessary upstream infrastructure upgrades. Such coordination efforts should begin preemptively to avoid delays. Forecasting ZET market development and planning will help minimize delays and reduce soft costs. Some technology-specific considerations include:
  - *Fast charging:* Develop a long-term (+5 year) fleet electrification plan, consulting with local DISCOMS to assess distribution capacity and provide them with peak load requirements for a long-term electrification plan.
  - *Ultra-Fast charging:* Engage with DISCOMS to plan for the requisite grid upgrades based on the expected charging peak load and work to develop managed charging plans.
  - *Battery Swapping:* Swapping stations can be optimally placed to provide en-route charging, in this analysis it was deemed that placing swapping stations every 50km was appropriate to alleviate range anxiety. Swapping stations should also ideally be located near substations, where there is spare grid capacity to minimize electrical expenditure.
  - *Catenary & Dynamic Induction:* Catenary and induction segments should be provided along the length of the corridor and spaced appropriately to provide en-route charging incrementally. Segments should ideally be placed to minimize cost and facilitate charging where required, such as on the outskirts of Delhi where there is heavy truck traffic.
  - *Hydrogen:* The development of regional hydrogen production clusters to generate and use hydrogen on-site for trucking activities can be a cost-optimal approach, ideal sites are those with a strong economic case for low-cost electrolysis through solar energy generation.

The figure below represents the time horizon of conducting each pass among the differing technologies.

Figure 26: Roadmap and time horizon of ZET by technology class

Yellow: Ideation Phase, Green: Planning Phase, Orange: Pilot Phase, Blue: Scaling Phase								
	2023	**2025**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Fast charging								
Ultra-Fast Charging								
Battery Swapping								
Catenary								
Induction								
H2 ICE								
H2 FCET								

Overall, ZET adoption presents a significant opportunity for India to achieve sustained fuel cost savings, reduce logistics expenses, and enhance energy security. This aligns with India's vision of self-reliance and positions the country to become a global leader in clean freight transportation. To realize these benefits on an accelerated timeline, fostering cohesive partnerships between the private and public sectors is crucial. These partnerships can facilitate the deployment of ZETs, the development of necessary infrastructure, and the creation of favorable market conditions. India possesses several advantages, including its existing EV-supportive policy frameworks, a well-established manufacturing sector, and a thriving ecosystem of dynamic startups. Leveraging these strengths, India can position itself as a global leader in low-cost, low-carbon freight movement.

Acknowledgements

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We would like to express our sincere appreciation to Indian Highway Management Company Limited (IHMCL) for their invaluable data contributions that significantly enhanced our report for techno-economic analysis.

Appendix

Appendix A: Delhi-Jaipur truck numbers

Infrastructure investment is dependent on the number of trucks and trucking activity along a highway. To strategically develop the Delhi-Jaipur corridor as a lighthouse corridor, it is essential to deploy infrastructure to meet the future demand for Zero-Emission Transportation along this corridor. This will ultimately lead to a high utilization rate and concentrated investment.

A two-part approach was deployed to assess trucking activity and the number of trucks. First, interviews were conducted with stakeholders, including OEMs, dealerships, fleet operators, EVSE providers, and E-Commerce companies, to gather estimates for the number of trucks making round trips along the Delhi-Jaipur highway. Secondly, granular data from Kherki Daula, Shahjahanpur, Manoharpura, and Daulatpura toll plazas was collected by the Indian Highway Management Company Limited (IHMCL) to assess truck traffic patterns and volume. In this section, Kherki Daula is referred to as toll plaza #1, Shahjahanpur as #2, Manoharpura as #3, and Daulatpura as #4, all depicted in Figure 27. The data was anonymized, and information on the vehicles' documented toll plaza crossing times and segment types were recorded.

Figure 27: Map of toll plazas

The following insights were found from expert stakeholder interviews and IHMCL toll data:

The derived number of trucks: The approximate stock of trucks traveling between Delhi and Jaipur is around 5,500. This number was derived by conducting over 28 interviews with OEMs, dealerships, fleet operators, EVSE providers, and E-Commerce companies, to gather estimates for the number of trucks making round trips along the Delhi-Jaipur highway.

Round trip variations: Approximately 70% of the trucks along the Delhi-Jaipur corridor regularly make round trips near Kherki Daula (toll plaza 1) and Shahjanpur (toll plaza 2), while only 7% complete the entire Delhi-Jaipur round trip. This distribution aligns with the presence of industrial townships, manufacturing plants, and construction aggregate plants in the area.

Distance traveled: A Delhi-Jaipur truck travels 223km on average daily, shown in figure 28. This is calculated based on the number of trucks making each round-trip travel pattern, and the average vehicle kilometers traveled (VKT) for each pattern, is summarized in the table below. The weighted average VKT was utilized to justify the modeled duty cycle to derive the truck vehicle cost documented in Appendix B.

Figure 28: Daily VKT based on traffic data

Round trip pattern	Percentage of trucks	Average VKT (km)
1-2-3-4-4-3-2-1	9.0%	300 (600km for 10% of trucks)
1-2-3-3-2-1	9.0%	260 (520km for 10% of trucks)
2-3-4-4-3-2	1.2%	170
1-2-2-1	0.7%	200
2-3-3-2	5.3%	60
3-4-4-3	36.5%	200
Only in toll plaza 1	23.2%	200
Only in toll plaza 2	12.6%	300
Only in toll plaza 3	2.6%	160
Only in toll plaza 4	0%	NA

Appendix B: Vehicle costs

Vehicle costs are calculated in different ways for battery electric trucks, hydrogen trucks, and diesel trucks. This appendix includes common input for all vehicle types and then details the assumptions behind the cost calculations of each truck technology.

Common assumptions

Common assumptions on vehicle characteristics and loan structure for vehicle lending are included in figure 29 below.

Figure 29: Estimating VKT along the corridor

Category	Input	Value	Explanation
Vehicle characteristics	Daily range assumed for modeling (km)	300	Based on the length of the Delhi-Jaipur corridor and the industry average VKT from toll data, our model used a conservative approach to estimate the total average range.
	Truck lifespan (years)	10	Based on industry interviews and vehicle kilometers traveled
	Operating days in a year (days)	350	Based on the industry average
	Average speed (km/hr)	60	Based on the industry average
	Truck size (tonnes)	HDT: 31 tonnes MDT: 12 tonnes	IHMCL classifies trucks based on the number of axles and GVWR. By assessing truck traffic by axel and weight classification, this analysis was able to induce that roughly 50% of truck traffic volume can be classified as an MDT while the other 50% can be classified as an HDT. The subsequent truck sizes were then derived to represent a market average.
	Loan term (years)	5	Based on the market average
Financing	Debt ratio	80%	Based on the market average
	Diesel vehicle interest rate and discount rate	9%	Based on the market average
	ZET interest rate	15%	Based on the market average, it is higher than the diesel interest rate because of the nascency of the technology.
	Uniform discount rate	15%	To derive the net present value and amortise operating costs a set discount rate was utilized
Conversion factor	Currency Conversion is used in modeling when applicable	USD 1 = INR 82.74	When cost data was given in USD a conversion factor was utilized

Truck operational efficiency

Calculating energy efficiency was a crucial step in determining each vehicle's overall fuel efficiency, which directly affects the fuel cost of each truck technology. Efficiency was derived from the average market efficiency rates as shown in figure 30 below.

Figure 30: Average efficiency factors of different Trucking technologies[51,52,53,54]

Percentage	Efficiency
Electric efficiency (%), a combination of battery and electric motor efficiency	85%
Fuel cell efficiency (%), a combination of fuel cell and electric motor efficiency	40%
Diesel drivetrain efficiency (%)	32%
CNG drivetrain efficiency (%)	29%
H2 ICE drivetrain efficiency (%)	32%
Regenerative braking (%)	10%

Vehicle cost elements across all technologies

The following elements were considered while calculating vehicle costs:

- Vehicle Purchase Cost: This includes down payment, principal, and interest costs for all MDT and HDT use cases. These were modelled through either a market assessment or a bottom-up cost assessment for each technology.
- Fuel Costs: For ZETs and diesel vehicles, fuel expenditure was determined by multiplying the one-year average cost of diesel, CNG, electricity rate, or hydrogen fuel price by the average vehicle efficiency and the annual kilometers traveled.
- Maintenance: Derived based on the market average diesel maintenance costs lowered based on expected market declines.
- Insurance: Calculated as a percentage of the vehicle cost, which varied by technology, and depreciated over the vehicle's useful life.
- Battery Replacement: This element applies exclusively to ZETs. Battery life and cycles were evaluated to determine the need for battery replacement and the associated cost.
- Toll costs tax and Registration: Taxes and registration were not considered in the truck TCO as trucks are licensed and travel between various states, since a market average cannot be reasonably ascertained this is not included in the model.

BET

Vehicle purchase cost. The total BET vehicle cost was derived from estimating the battery cost plus the cost of the truck itself. The following six-step process outlines how the vehicle cost was derived per the differing BET technologies.

Step 1: Calculate the battery size needed. The baseline battery capacities are determined based on the efficiency of electric vehicles, while also considering State of Charge (SoC) and State of Health (SoH) allowances. The SoC allowance considers that the energy drawn from the battery for every cycle will be lower than the total capacity. We have assumed this to be 85%. The SoH allowance takes into account the overall battery health before it becomes unusable for mobility applications. Typically, this is a point when battery capacity reaches 80%

of its original capacity, hence this allowance is 80%. Finally, the battery capacity is calculated as follows: Range*Efficiency/ (SoC allowance*SoH allowance). These baseline capacities were then calculated to provide a 300 km range for MDTs and HDTs, as shown in Figure 31 below.

Figure 31: Baseline battery size expressed in kWh

Vehicle segment and adoption scenario	Range (km)	Efficiency (kWh/km)	Battery size, including allowances (kWh)
MDT-Pilot	300	0.8	351
HDT-Pilot	300	1.4	616

Step 2: Adjust the battery size for the differing BET technologies based on infrastructure placement and operability. Based on the BET technology, the baseline battery size was downsized when en-route charging could be accommodated.

Ultra-Fast Charging and Battery Swapping: In the 2025 pilot phase, it was assumed that the battery sizes for these technologies must meet the 300 km range requirement. However, with scaled deployment expected by 2030 and the availability of en-route charging options (six charging/battery swapping hubs located approximately 50 km apart, as described in detail in Appendix C), it was assumed that the battery size could be smaller.

Catenary and induction Catenary and Induction trucks, equipped with the ability to charge en-route while in motion, allow for a reduction in battery size to account for en-route charging availability. Based on the energy transfer capabilities described in Appendix C.

Figure 32: Derived battery sizes for the differing BET technologies

Technology	Pilot scale assumed battery size	Scalded deployment battery size
Fast Charging Depot	MDT: 353 kWh HDT: 618 kWh	MDT:353 kWh HDT: 618 kWh
Ultra-fast charging	MDT: 353 kWh HDT: 618 kWh	MDT: 235 kWh HDT: 408 kWh
Swapping	MDT: 353 kWh HDT: 618 kWh	MDT: 235 kWh HDT: 408 kWh
Catenary and dynamic induction	MDT: 180 kWh HDT: 377 kWh	MDT: 117 kWh HDT: 205 kWh

Note: Catenary and dynamic induction battery size was accounted for, based on the energy delivered to the battery from the en-route charging mechanism, however, a minimum battery size was held as a floor to ensure a truck could at a minimum 100km battery range to allow traversing outside of the corridor.

Step 3: Derive the total battery cost by technology The battery price for 2025 was estimated at 18,919 INR/kWh, based on the Indian market average, while the price for 2030 was projected to be 10,776 INR/kWh, considering price convergence toward the global average battery price.[55] Using these two price forecasts, the total battery cost for Battery Electric Trucks (BETs) for the pilot in 2025 and scaled deployment in 2030 was calculated by multiplying the battery size by the respective price.

Step 4: Derive the balance of the truck cost. The balance of truck cost includes the cost of truck chassis, power electronics, onboard charger, thermal management system, etc., which remains constant across all technologies. A marginal linear price decline was modeled based on economies of scale.

Figure 33: The balance of truck cost plus any additional CAPEX costs

Year	2025	2030
Balance of truck cost for HDT	INR 44 Lakh	INR 42.8 Lakh
Balance of truck cost for MDT	INR 19 Lakh	INR 18.4 Lakh

Step 5: Derive any additional costs. The vehicle cost of Catenary and Dynamic Induction trucks includes additional hardware installed on the truck to draw power from catenary wires and Dynamic Induction coils, as summarized in the table below.

Figure 34: Additional CAPEX cost for Catenary and Dynamic Induction Trucks[56]

Cost of equipment	Pilot scenario (2025 equipment cost)	Scaled deployment (2030 equipment cost)
Catenary (Pantograph)	INR 17.5 Lakh	INR 7.9 Lakh
Dynamic Induction (coils on trucks)	INR 9.5 Lakh	INR 8.9 Lakh

Step 6: Derive the total vehicle cost based on the assumed loan structure. The vehicle cost comprises three main components: 1) BET battery cost, 2) balance of truck cost, and 3) any additional cost elements. These vehicle costs for all BET technologies are incorporated into down payment, interest, and principal calculations based on a 5-year loan with an 80% debt ratio and a 15% interest rate.

Fuel/Recharging cost: BET fuel cost is determined by the electricity price, annual distance driven, and battery efficiency. The electricity price for BET recharging for the pilot in 2025 was set at 5 INR/kWh, which represents the Indian average state EV tariff in Delhi and Rajasthan. By 2030, the charging tariff is assumed to increase to 7.5 INR/kWh as the EV tariff is phased out, and trucks are subject to the industry average tariff price. Electricity prices remain constant across all BET technologies.

Battery replacement: Battery replacement costs are factored into the overall vehicle cost due to batteries having a shorter lifespan than the vehicle itself. This is mainly because batteries become inefficient for trucking applications when their capacity drops to 80% or lower, necessitating replacement. Through extensive industry interviews, the number of battery cycles, i.e., the number of times a battery can be recharged before reaching an 80% state of health, was determined. Over time, as technology improves, the analysis accounts for a gradual linear increase in the battery state of health. The lifetime battery range is calculated by multiplying the number of charging cycles by the battery range. Finally, the battery replacement schedule is derived based on the lifetime battery range and vehicle lifetime kilometres traveled.

Figure 35: Battery cycling schedule by year

Year	2025	2026	2027	2028	2029	2030
Number of charging cycles before a battery reasonably reaches an 80% state of health	2667	2800	2933	3067	3200	3333

Across both scenarios, battery electric trucks require one new battery during the 10-year operating period, typically between year 7 and year 9. The assumption is that the battery replacement cost is included in the vehicle cost for battery swapping. In contrast, the replacement cost for spare batteries at swapping stations is considered part of the infrastructure cost. This battery replacement schedule is applied consistently across all BET technologies.

Maintenance: ZET maintenance costs are determined based on diesel maintenance costs. It was assumed that there would be a learning curve and higher maintenance expenditure due to a shortage of skilled service technicians, replacement of parts instead of repairs and limited parts availability in 2025 for ZETs. However, as the technology matures, with fewer moving parts compared to an ICE truck, maintenance costs will gradually decrease. They are projected to reach parity with ICE maintenance costs by 2027 and become lower than ICE maintenance costs from that point onward.

Figure 36: ZET maintenance cost percentage compared to diesel

	2025	2026	2027	2028	2029	2030
Percentage of Diesel maintenance cost	120%	120%	80%	80%	80%	60%

Hydrogen

As mentioned above, hydrogen trucks encompass vehicle purchase, fuel, maintenance, and fuel cell replacement (applicable only to fuel cell hydrogen trucks and not ICE hydrogen trucks). The vehicle purchase cost of H2 ICE and fuel cell hydrogen trucks includes the balance of truck and powertrain components, as shown in figures 37 and 38 below.

Figure 37: The vehicle purchase cost of HDT Hydrogen ICE and Fuel cell trucks

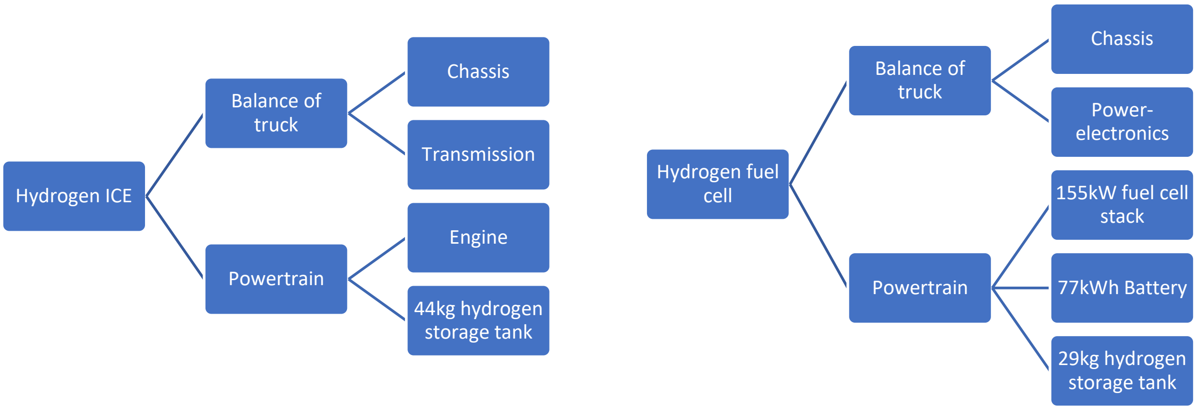
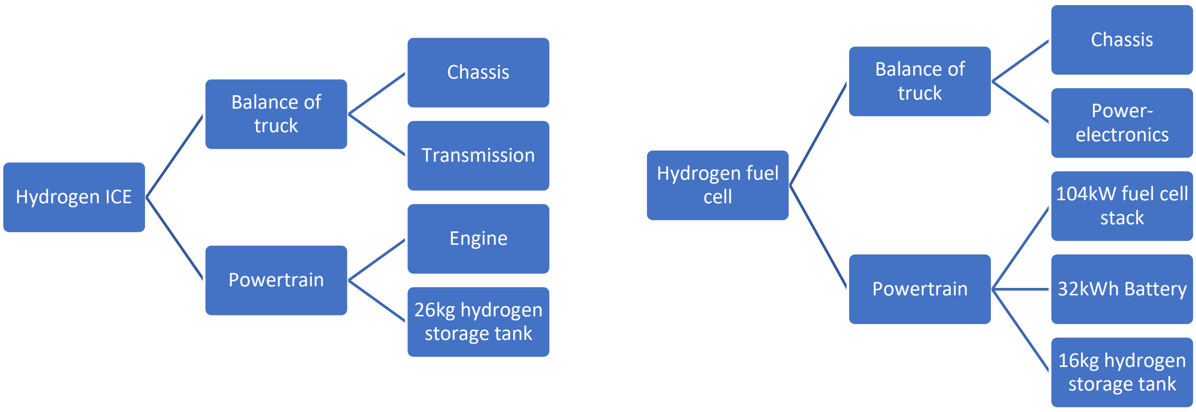


Figure 38: The vehicle purchase cost of MDT Hydrogen ICE and fuel cell trucks



The balance of the truck of an H2 ICE includes the chassis and transmission, which is the same as that of a diesel truck. The powertrain for H2 ICE comprises the engine and the H2 storage tank. For H2 ICE, the engine cost is the same as the diesel engine, with the addition of Selective Catalytic Reduction (SCR) after-treatment for NOx emissions. The main cost factor for H2 ICE is the onboard storage tank required for Delhi-Jaipur operations, increasing the truck's overall price.

For FCETs, the truck's balance includes the chassis and power electronics. The powertrain costs for FCETs are quite substantial due to the expensive fuel cell stack, the additional battery needed to manage intermittency, and the onboard storage tank. Once the fuel cell, storage tank, and battery sizes are estimated, they are multiplied by the per-unit fuel cell price ($/kW), storage tank price ($/kg), and battery price ($/kWh), respectively, to calculate the total powertrain cost. Finally, the truck and powertrain costs are added together to derive the total upfront price.

Figure 39: Key input used in hydrogen truck cost calculations are summarized in the table below

Particulars	HDT		MDT	
Metric	H2 ICE	H2 FCET	H2 ICE	H2 FCET
Fuel economy (km/kg)	8.1	12.6	14	22.15
Onboard storage tank (Total capacity) (kg)	44	29	21	14
Onboard storage tank (Usable capacity) (kg)	37	24	26	16
Fuel cell size (kW)	N.A.	155	N.A.	104
Battery size (kWh)	N.A.	69	N.A.	32
Onboard storage tank cost (INR/kg) - 2025	61875			
Onboard storage tank cost (INR/kg) - 2030	49500			
Fuel cell cost (INR/kW) - 2025	N.A.	67733	N.A.	67733
Fuel cell cost (INR/kW) - 2030	N.A.	28875	N.A.	28875
Vehicle purchase cost – 2025 (INR)	61 Lakh	1.7 Crore	34 Lakh	1 Crore
Vehicle purchase cost – 2030 (INR)	58 Lakh	1 Crore	35 Lakh	58 Lakh

Note: N.A indicates a cost that is not applicable for a specific technology, specifically H2 ICE vehicles do not have a fuel cell thus this cost was not included.
Fuel costs: For H2 trucks, fuel costs are a factor of green hydrogen price (INR/kg), vehicle efficiency (km/kg), and annual distance driven.

The H2 production cost is estimated by assuming there will be a central green hydrogen production plant in Rajasthan, equidistant (150 km) from the two endpoints of the Delhi–Jaipur corridor. The levelized cost of H2 production includes capital expenditure on electrolyser, solar panels to produce electricity for powering the **electrolyser**, operation and maintenance related to **electrolyser**, **electrolyser** stack replacement, and GST.

The price of green hydrogen delivered at the refueling station includes three main components:

- **H2 production cost**: The H2 production cost is estimated by assuming there will be a central green hydrogen production plant in Rajasthan, equidistant (150 km) from the two endpoints of the Delhi–Jaipur corridor. The levelized cost of H2 production includes capital expenditure on **electrolyser**, solar panels to produce electricity for powering the **electrolyser**, operation and maintenance related to **electrolyser**, **electrolyser** stack replacement, and GST.
- **H2 storage cost**: This is the cost to store H2 in pressurized containers at the site of production.
- **H2 transport cost**: H2 is transported via trucks with tube trailers, as pipelines are not considered economical for shorter distances. The cost components include vehicle

CAPEX, fuel, and maintenance for a round trip between the H2 production plant and refueling stations.

Figure 40: H2 Price breakdown

H2 price breakdown (INR/kg)	2025	2025	2026	2027	2028	2029	2030
Production	269	239	215	195	178	163	149
Storage	171	166	162	157	152	147	142
Transport	46	42	40	37	36	34	33
Final H2 price	486	448	417	389	365	344	325

H2 FCETs are more efficient than H2 ICE trucks as they utilize a combination of fuel cells and electric motors, which are more efficient than the internal combustion engines used in H2 ICE vehicles. The vehicle efficiencies for H2 FCETs have been estimated based on an extensive market survey of models available globally, aligning with range and payload requirements typical for the Indian market, especially along the Delhi–Jaipur corridor. Efficiencies for H2 ICE are estimated based on expert interviews.

Maintenance: Based on expert interviews, H2 ICE maintenance costs are assumed to be 25% more than diesel and equivalent to CNG. H2 FCET maintenance costs are assumed to be 4% higher than BET maintenance costs.

Fuel cell replacement cost: Fuel cell life is defined in terms of the number of operating hours of the stack. Depending on the daily operational hours and vehicle life, the total operational hours of the truck are estimated. Total operational hours are divided by fuel cell life hours (20,000 hours in 2025 and 25,000 hours in 2030) to estimate how many fuel cells are required over the life of the vehicle and when they need replacement. On the Delhi-Jaipur highway, the analysis shows that FCET trucks operating on the Delhi-Jaipur corridor and purchased between 2025 and 2030 need to replace their fuel cell stack once before the end of their lifetime. The cost is derived from 50% of the fuel cell price (INR/kW) when replacement is due and multiplied by the stack size (kW) based on expert interviews.

CNG and Diesel truck cost

For diesel trucks a more preferential lending rate was utilized, 9%, over 5 years and 80% LTV, maintenance costs were then amortized using a 15% discount rate. The capital cost of diesel or a CNG truck cost includes purchase costs (reflected in down payment, principal, and interest), fuel costs, maintenance costs, and insurance. Detailed input for the diesel and CNG truck cost calculation is summarized in figure 41 below.

Figure 41: Diesel truck cost breakdown

Input	MDT Value CNG truck	HDT Value Diesel fuel truck	Assumption
Vehicle purchase cost – 2025 (INR)	19.5 Lakh	30.8 Lakh	Derived from the average price of diesel trucks in the Indian market today for HDT use cases, a linear price increase is assumed, as prices increase on account of regulatory scrutiny
Vehicle purchase cost – 2030 (INR)	22.8 Lakh	36 Lakh	Derived from market average truck costs, a linear price increase is assumed, as prices increase on account of regulatory scrutiny.
Fuel cost in 2025 INR/kg or (INR/L)	80 INR/kg	88 INR/L	The one-year average price of diesel from April 2020-April 2021 in India
Fuel cost in 2030 INR/kg or (INR/L)	85 INR/L	93 INR/L	1% real price increase year over year
Maintenance cost of diesel (INR/km)	1.3 INR/km	2 INR/km	Derived based on market interviews and a 2% linear price increase year over year.
Maintenance cost of diesel (INR/km)	1.6 INR/km	2.4 INR/km	Derived as 120% of the cost of diesel
Insurance (% of vehicle depreciation value)	NA	NA	3% of the vehicle depreciation value. Straight-line depreciation, 0 salvage value

Appendix C: Infrastructure costs

The infrastructure cost encompasses the expenses for deploying charging or refueling assets to accommodate the total number of corridor trucks. This cost includes upfront expenses, maintenance, and additional batteries for battery swapping. For all seven technologies, upfront costs, which include hardware and installation expenses, are considered as part of the down payment, principal, and interest. This is because the capital costs of the infrastructure are assumed not to be covered outright but are instead financed with a 9% interest rate, a 20% down payment, and a 15-year loan term. The operational costs of the infrastructure are discounted to today's value using a 9% discount rate. Infrastructure was sized based on the charging and refueling needs of HDTs and MDTs separately.

The tables and maps below provide details on how infrastructure was deployed in 2025 and 2030 to support ZET mobility and outline the costs associated with its deployment. The analysis takes into consideration the charging and refueling requirements based on truck traffic patterns, range requirements, and charging time. Infrastructure assets are then planned to meet this demand and deployed at hubs or stations along the corridor.

Figure 42: Charing or refueling hub placement in the pilot for 100 ZETs in 2025

Hub Name	Nearest toll plaza	Nearest truck stop	Nearest substation	Placement Rational
Bhiwadi, Servicing Greater Delhi	Kherki Dula	Bhiwadi	Bhiwadi	A charging hub is required for trucks concluding their trips near Delhi and Jaipur. A hub in both nodal cities is the minimum infrastructure requirement.
Jaipur	Jaipur	Jhotwara	Kukas	
Neemrana	Shahjahanpur	Neemrana	Neemrana/Behror	Located centrally, this is a major industrial cluster experiencing a large volume of truck traffic.

Figure 43: Delhi-Jaipur corridor map of charging hubs, substations, and truck stops

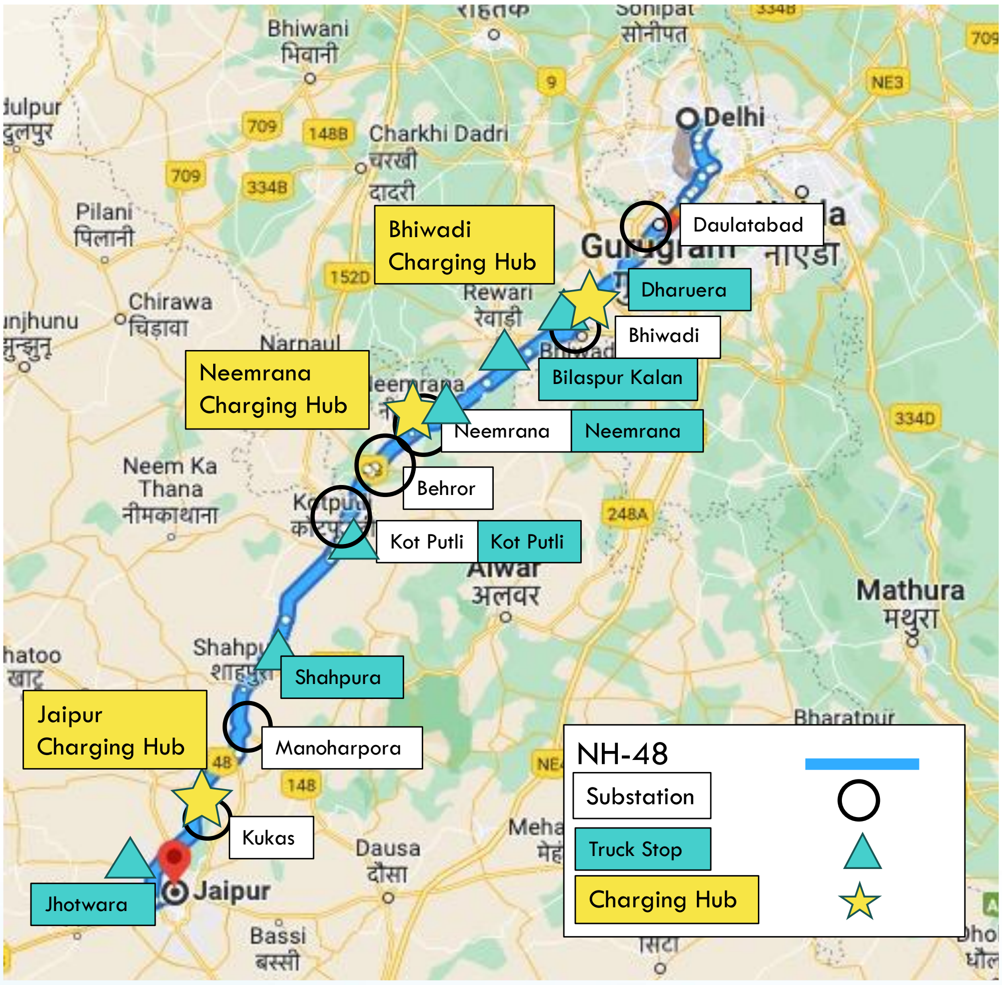
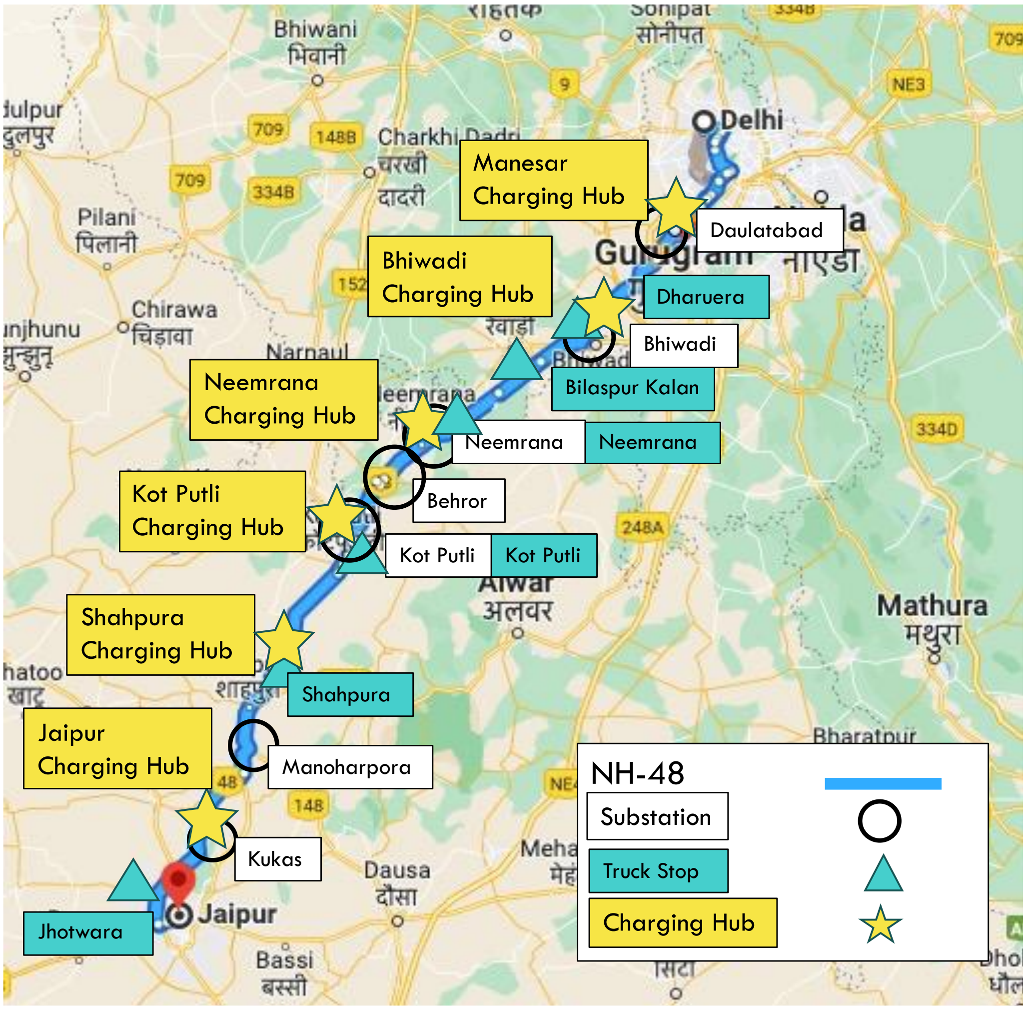


Figure 44: Charging and or refueling hub placement in 2030 for 5,500 ZETs

Hub Name	Nearest toll plaza	Nearest truck stop	Nearest substation	Rational
Manesar, Servicing Greater Delhi	Kherki Dula	Dharuera	Daulatabad	Given the high volume of truck traffic in, around, and through greater Delhi, two charging hubs are required to fully meet charging or refueling needs.
Bhiwadi, Servicing Greater Delhi	Kherki Dula	Dharuera	Bilaspur Kalan	
Neemrana	Shahjanpur	Neemrana	Neemrana	This is a major industrial cluster experiencing a large volume of truck traffic.
Kotpulti	Shahjanpur	Kotpulti	Kopulti	Charging/refueling stations are located every ~50km to minimize range anxiety. Kotputli is a hub for construction aggregators.
Shahpura	Manoharpura	Shapura	Manoharpura	Charging/refueling stations are located every ~50km to minimize range anxiety. This station enables operators traveling between Delhi and Jaipur to have an option en-route to charge.
Jaipur	Daulatpura	Jhotwara	Kukas	A charging hub is needed for trucks ending their trips near Jaipur.

**Note: the analysis seeks to site roughly ~50km apart near substations, and major trucking stops to facilitate seamless ZET mobility and alleviate any range anxiety.*

Figure 45: Map of the charging or refueling hub placement in scaled deployment by 2030



Based on the combinations or the differing trips along the Delhi-Jaipur corridor obtained from IHMCL data, this analysis sought to understand the percentage of truck volume at a hub and the required charging or refueling infrastructure needed to adequately charge or refuel trucks based on the estimated traffic volume. Based on the amount of infrastructure required at each hub, charging infrastructure cost was estimated per each technology presented in the tables and sections to follow.

Fast Charging at depots

This analysis sought to derive the percentage of truck traffic requiring a full charge during an overlapping charging period based on the charging time (6 hours for HDT, 3.5 hours for MDTs). Next, truck traffic data was analyzed to understand the percentage of truck traffic needing to charge during a coincident period at a given charging hub. The number of chargers was taken to be equal to the percentage of truck traffic that may need to charge during a coincident charging period multiplied by the number of trucks along the corridor.

Figure 46: The number of fast chargers required to facilitate charging in 2025 (Pilot phase)

Pilot	Chargers to meet pilot HDT power requirements	Chargers to meet pilot MDT power requirements
Bhiwadi	23	16
Neemrana	7	5
Jaipur	7	5
Total Chargers needed	**37**	**26**

Figure 47: Total cumulative fast chargers required through 2030 to accommodate scaled deployment

Scaled deployment	Chargers to meet pilot HDT power requirements	Chargers to meet scaled deployment MDT power requirements
Manesar, Servicing Greater Delhi	643	448
Bhiwadi, Servicing Greater Delhi	643	448
Neemrana	379	249
Kotpulti	120	78
Shahpura	120	78
Jaipur	145	106
Total Chargers needed	**2050**	**1406**

Once the number of chargers was determined, the unit costs for installing such chargers were derived. A size of 100 kW was assumed for the fast charger, as this allows HDT charging in under 8 hours, which was established as the maximum allowable charge time. Figure 48 summarizes the input for calculating fast-charging hardware, installation, and maintenance costs.

Figure 48: Fast charger unit costs

Input	Value	Assumption
Charger hardware cost in 2025 (INR)	20 lakhs	Based on market research and interviews with charging operators in India
Installation cost	20% of hardware	Based on market research
Maintenance cost	5% of hardware amortised annually	Based on market research.

Ultra-Fast Charging

To assess the needed charging assets for Ultra-Fast Charging, this analysis correlated charging hub placement with toll plaza proximity to estimate truck traffic. The analysis involved the examination of truck traffic data of an average day to ascertain the maximum number of corridor trucks that might need to be charged at respective hubs during a specific hour. Based on the charger size in pilot and scaled deployment examples the time it takes to charger was derived. The number of chargers at a hub was then derived based on the percentage of truck traffic that may need to be charged at a hub and the charging time to derive the number of charges. The figures below depict the charge sizes utilized, and the number of chargers at a given hub.

Figure 49: Charger size and description

Input	Value	Description
Charger size in 2025 (Pilot)	240 kW	Based on the maximum allowable charge time of 2-3 hours and the technology available today
Charger size in 2030 (Scaled Deployment)	500 kW	Assuming technology advances the design, the parameter was based upon a maximum allowable charge time of 1.5 hours

Figure 50: The number of ultra-fast chargers required to facilitate charging in 2025 (Pilot phase)

Hub name and location	Chargers to meet pilot HDT power requirements	Chargers to meet pilot MDT power requirements
Bhiwadi, Servicing Greater Delhi	16	12
Neemrana	10	7
Jhotwara servicing greater Jaipur	5	3
Total chargers needed	**31**	**22**

Figure 51: Total cumulative ultra-fast chargers needed through 2030 to accommodate scaled deployment

Hub name and location	Chargers to meet pilot HDT power requirements	Chargers to meet scaled deployment MDT power requirements
Manesar, Servicing Greater Delhi	110	63
Bhiwadi, Servicing Greater Delhi	110	63
Neemrana	121	70
Kotpulti	78	10
Shahpura	78	10
Jhotwara servicing greater Jaipur	106	16
Total chargers needed	**602**	**233**

The table below summarizes the input for calculating fast-charging hardware, installation, and maintenance costs. The number of chargers is the most important factor affecting the fast-charging infrastructure cost.

Figure 52: Ultra-Fast Charging hardware installation and maintenance costs

Input	Value	Assumption
240kw Charger hardware cost in 2025	34 lakhs	Based on market research and interviews with charging operators in India
500kw Charger hardware cost in 2030	48 lakhs	Extrapolated from market interviews and derived per market rate price decline
Installation cost	20% of hardware	Based on market research
Maintenance cost	5% of hardware amortised annually	Based on market research.

Battery Swapping:

Similar to the charging technologies, an approximation of percentages of trucks that cross each swapping hub has been identified based on the IHMCL toll data. The maximum number of trucks that pass through each hub within an hour is then calculated by multiplying the percentages by the total number of 5500 trucks. The number of spare batteries needed in each charging hub is then calculated using the formula below:

Number of spare batteries in a swapping hub = Battery Size (kWh) * (1-24%) / 300kW * Maximum number of trucks that cross the swapping hub in an hour;300kW is the charger power in swapping stations, and 24% is the battery state of charger before swapping. The number of spare batteries in each charging hub is summarized in the table below.

Figure 53: Number of spare batteries in each charging hub

		Manesar Hub	Bhiwadi	Neemrana Hub	Kotputli Hub	Shahpura Hub	Jaipur Hub
MDT	Pilot	NA	6	4	NA	NA	3
	Scaled development	99	99	115	33	33	33
HDT	Pilot	NA	10	7	NA	NA	5
	Scaled development	171	171	200	57	57	57

Note: At the pilot scale, only three hubs are required to meet requisite charging demand, thus, Manesar, Kotputli, and Shapura are deemed only necessary upon scaled deployment when there is a greater number of trucks that will require charging demand, thus at the pilot scale these sites are listed as NA.

It is then assumed that each truck takes around 10 mins to complete one swap, and therefore one station can provide 6 swaps within an hour. The number of swapping stations in each hub is then calculated assuming that each swapping station has 6 spare batteries. Finally, the

CAPEX and OPEX battery swapping infrastructure can be derived based on the number of swapping stations and spare batteries. Since batteries have a shorter lifespan than the swapping infrastructure, battery replacement cost is included in the cost of spare batteries.

The figure below summarizes the input for calculating battery swapping hardware, installation, and maintenance costs. Since China is the only market with commercial-scale battery-swapping highway corridors for electric trucks, the operational data from China's three battery-swapping highway corridors serve as an important basis for developing the cost calculation methodology for the Delhi-Jaipur corridor.

Figure 54: Battery replacement cost calculations

Input	Value	Assumption
Swapping station cost in 2025 (INR)	463.1 Lakh	2025 price decreases by 2% per year to 2030 price.
Swapping station cost in 2030 (INR)	411.2 Lakh	Equals to China's swapping station cost today.[57]
Swapping station power (kW)	300	Based on the power used in China's truck-swapping stations today[58]
Battery state of charge before swapping	24%	Based on China's market data[59]
Installation cost	5% of hardware	Based on China's market data[60]
Maintenance cost	5% of hardware	Based on China's market data[61]

Catenary and Dynamic Induction:

While catenary and Dynamic Induction are functionally different systems in terms of their power transfer, the overhead wires, or underground coils function similarly in the sense of how they are deployed and where they may span along the length of the corridor.

In the 2025 pilot phase, it was assumed that three stretches of 10 km of coils or wires would be deployed. In the scaled deployment planned for 2030, the design accounted for an additional 50km of wires and coil to be installed. With a total of 6 segments or 80 km of catenary wires or induction coils spanning the corridor in either direction. The analysis aims to employ a segmented infrastructure configuration to minimize costs, as it allows wiring or coils to be placed in optimal locations to reduce construction and civil works expenses. The second objective is to distribute power to maximize the charging potential of trucks en-route.

Figure 55: Infrastructure configuration, power delivery, and energy supply for the pilot in 2025

HDT	MDT		
Deriving time of charge (Distance km) * Average speed (km/h) = Time spent driving under the catenary wire	**Charging Time**	**Unit**	**Description**
60	60	km/h	Vehicle speed
30	30	km	Total segment length
0.5	0.5	h	Time a truck was able to enroute charge
Constants	**Constants**	**Unit**	**Description**
1.4	1.4	kWh/km	Truck Energy consumption per km
1500	1500	V DC	Voltage in overhead wire or coil. The voltages modeled are idealized and reflective of modeling for maximizing power transfer. Alterations in the voltage delivered to catenary trucks may differ based on local grid constraints.
350	250	Amps	Current in the line drawn from pantograph truck specific
Infrastructure Power delivery	**Infrastructure Power delivery**	**Unit**	**Description**
472	337	kW	Power delivered
75	75	kW	Traction power to power electric engine
397	262	kW	Power available to charge the battery
Infrastructure Energy delivery	**Infrastructure Energy delivery**	**Unit**	**Description**
~200	~131	kWh	Energy is delivered to the battery along the length of the corridor

Note: current, 350 amps was ascertained as the maximum amount of power that pantographs given

Figure 56: Infrastructure configuration, power delivery, and energy supply for scaled deployment

HDT	MDT		
Deriving time of charge (Distance km) * Average speed (km/h) = Time spent driving under the catenary wire	**Charging Time**	**Unit**	**Description**
60	60	km/h	Vehicle speed
80	30	km	Total segment length
1.3	0.5	h	Time a truck was able to enroute charge
Constants	**Constants**	**Unit**	**Description**
1.4	1.4	kWh/km	Truck Energy consumption per km
1500	1500	V DC	Voltage in overhead wire or coil.
300[6]	200	amps	Current in a line drawn from pantograph truck specific
Infrastructure Power delivery	**Infrastructure Power delivery**	**Unit**	**Description**
260	270	kW	Power delivered from catenary
75	75	kW	Traction power needed for the engine
225	195	kW	Power available to charge the battery
Infrastructure Energy delivery	**Infrastructure Energy delivery**	**Unit**	**Description**
440	260	kWh	The energy delivered to the battery along the length of the corridor

[6] The current modeled was idealised based desired power transfer, the ability to adjust the amount of current based on charging needs of trucks needs to be considered when/if detailed engineering studies on deployment were to take place.

Figure 57: Unit costs of catenary hardware and installation

Input	Value	Assumption
Hardware cost and cost to install (INR/km)	6.97 Lakh	Based on extensive market interviews drawing on cost data from globally deployed pilots
Maintenance cost	2% of hardware cost amortised annually	Based on extensive interviews and a literature review of the global average cost to deploy overhead catenary wires. The maintenance was derived as a percentage of the hardware costs amortised annually over the life of the asset.

Figure 58: Dynamic Induction cost inputs estimate

Input	Value	Assumption
Hardware cost and cost to install hardware pilot (INR/km)	14.8 Lakh	Based on extensive market interviews drawing on cost data from globally deployed pilots
Hardware cost and cost to install hardware at scaled deployment (INR/km)	12.3 Lakh	Based on extensive market interviews drawing on cost data from globally deployed pilots
Maintenance cost	1% of hardware cost amortised annually	Based on extensive interviews and a literature review of the global average cost to deploy Dynamic Induction coils. The maintenance was derived as a percentage of the hardware costs amortised annually over the life of the asset.

Additional fast charging cost:

An additional cost for charging the batteries at both ends of the corridor is factored into the cost of catenary and Dynamic Induction infrastructure in the pilot phase. This is because such a charging solution cannot be deployed in isolation while accommodating the range of movement that Delhi-Jaipur trucks require. To account for this, the model considers that trucks need to start their corridor trip with a full charge, facilitated by charging at either end of the corridor. Thus, the pilot phase cost includes the expenses associated with deploying fast chargers at both nodal ends of the corridor.

Hydrogen

The key input related to hydrogen infrastructure cost is summarized in the table below. H2 station utilization is defined as the ratio of kg of H2 dispensed over the total H2 station capacity. Station CAPEX includes costs for hardware/equipment like compressors, storage tanks and dispensers and costs to install that hardware.

Figure 59: Hydrogen infrastructure cost figures for utilization, CAPEX, OPEX

Input	Value
H2 station utilization* in 2025	60%
H2 station utilization* in 2030	80%
H2 station CAPEX – pilot (Lakh INR/kg)	1.7
H2 station CAPEX – scaled deployment (Lakh INR/kg)	1.2
H2 station OPEX	5%

Infrastructure sensitivity

Hardware costs and maintenance costs have significant impacts on the total infrastructure cost. The cost analysis above illustrates the average cost scenario, which represents the price estimates derived from market trends thus far. This report also includes a sensitivity analysis of the high-cost scenario, which represents a case where costs are higher than anticipated due to the myriad of variables that directly and indirectly affect the cost, such as labor, supply chain bottlenecks, slow technology adoption rates, etc. Figure 60 summarizes the different inputs in the average cost and high-cost scenarios.

Figure 60: Sensitivity analysis input for ZET technologies

	Average modeled cost	Higher cost scenario
Fast charging	• Per Kw Indian market avg. price • 5% of CAPEX as maintenance cost	• Per Kw Indian market avg. price with a mark-up factor of 1.3 • 10% of CAPEX as maintenance cost
Ultra-Fast Charging	• Per Kw Indian market avg. price • 5% of CAPEX as maintenance cost	• Per Kw Indian market avg. price with a mark-up factor of 1.3 • 10% of CAPEX as maintenance cost
Swapping	• Truck to spare battery ratio is calculated based on battery size and charger power, ranging from 0.2 to 0.4 • China's swapping station CAPEX today is India's price in 2030, with a 2% decrease from 2025 to 2030 • 5% of CAPEX as maintenance cost	• Truck to battery ratio equals 0.4 • Swapping station CAPEX in the average cost scenario with a mark-up factor of 1.3 • 10% of CAPEX as maintenance cost
Catenary	• 7 Lakh INR/km (USD 0.85 Million/km) • 2% of CAPEX as maintenance cost	• 9.2 Lakh INR/km (USD 1.1 Million/km) • 5% of CAPEX as maintenance cost
Dynamic Induction	• 12.3 Lakh INR/km or (USD 1.5 Million/km)	• 14.7 Lakh INR/km or (USD 1.8 Million/km)

	• 1% of CAPEX as maintenance cost	• 5% of CAPEX as maintenance cost
Hydrogen ICE and fuel cell	• \$2063/kg CAPEX in 2025, \$1418/kg in 2030 • 5% of CAPEX as maintenance cost	• \$2427/kg CAPEX in 2025, \$1670/kg in 2030 • 10% of CAPEX as maintenance cost

Land costs

A detailed assessment was conducted to determine the average land parcel cost. First, the cost of land within 2km of the highway was ascertained, as this was the approximate distance utilized to optimize for both land costs and relatively seamless refueling. Based on extensive stakeholder interviews, this value was derived to be INR 3,500 per square meter. The cost to procure land along the highway was also ascertained as catenary and dynamic induction systems would require such land; the average cost of such land was derived to be INR 10,000 per square meter.

The land parcel size required by technology was then calculated. The land size was derived as the minimum land requirement to support charging or refueling and was not inclusive of land required for maintenance access, the cost of land for electrical infrastructure upgrades, or land utilized for construction. Figure 61 below presents the required land to develop the requisite infrastructure at both the pilot and scaled deployment stages.

Figure 61: Land Area for ZET Infrastructure Technologies

Technology	Pilot Total area (m^2)	Scaled 2030 Total area (m^2)	Description
Fast charging	2,850	27,010	Space to park and charge required to meet truck charging demand
Ultra-fast	2,452	8,251	Space to park and charge required to meet truck charging demand
Catenary	30,000	50,000	Based on the length of the wires installed along the length of the corridor
Induction	30,000	50,000	Based on the length of the coils installed along the length of the corridor
Swapping	1,625	24,700	Detailed stakeholder interviews, based on the number of swapping stations
H2 - ICE	4,081	28,940	Detailed stakeholder interviews, based on CNG station size
H2 - FCET	2,607	18,490	Detailed stakeholder interviews, based on CNG station size

Based on the average land cost and parcel size, an investment figure was determined for each year from 2025 through scaled deployment to accommodate incremental infrastructure development to meet the growing demand for ZETs. The net present value of land costs was calculated based on the incremental investment figures derived for each technology. The derived incremental land costs were then modeled under the assumption that a loan was utilized to finance the land acquisition. The loan term was set at 10 years, with an interest rate of 9%. Subsequently, it was assumed that refueling providers would retain land ownership from 2025 to 2040, a period of 15 years, aligning with the modeled infrastructure asset life as previously described. The cost of lending, including interest and principal payments made, as well as the land valuation in year 15, were then discounted to present value and aggregated to determine the total cost of land.

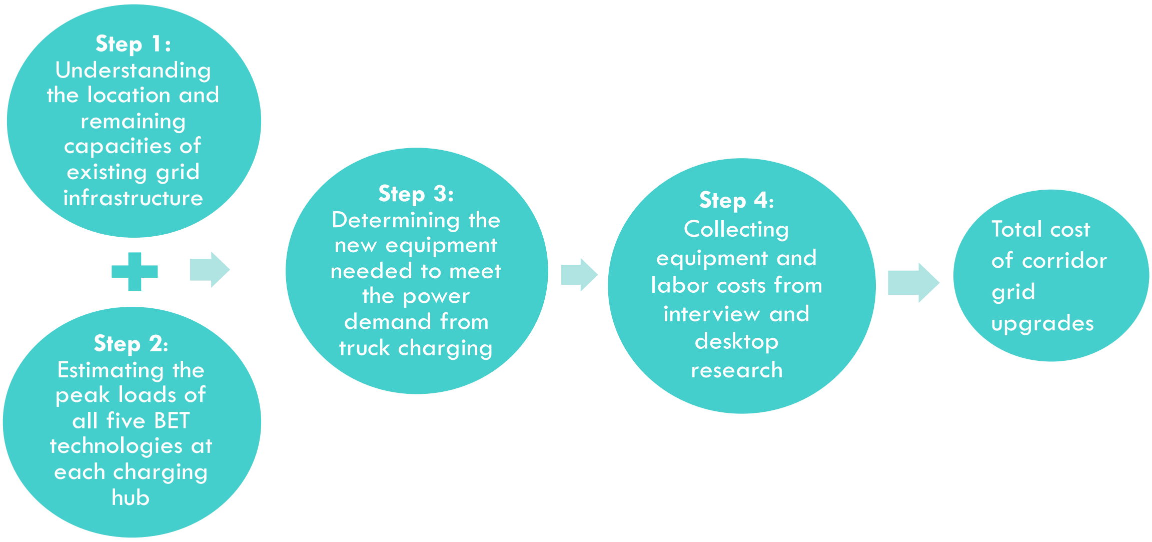
Based on the average land cost and parcel size, an investment figure was arrived at for each year from 2025 through scaled deployment to accommodate incremental infrastructure development to meet the growing ZET demand. The net present value of land costs was derived based on the incremental investment figures derived for each technology. The derived incremental land costs were then modeled based on the premise that a loan was used to pay for the land. The loan term was 10 years, with a 9% interest rate. Next, it was modeled that refueling providers then have to retain land ownership from 2025 to 2040, 15 years, which matches the infrastructure asset life modeled and described above. The cost of lending, the interest and principal payments made, and the land valuation (taken at 3% real compound increase) in year 15 were then discounted to present value and summed to arrive at the total cost of land.

Appendix D: Grid costs

The final component of the truck TCO is the upstream infrastructure cost, which refers explicitly to grid upgrade costs for BET charging. For hydrogen trucks, the production and transportation costs for hydrogen have been embedded in the fuel cost and are discussed at length in the vehicle cost section.

As shown in Figure 62 below, the total grid upgrade cost is calculated based on a four-step approach. First, data on the existing grid infrastructure's location and remaining capacities are collected through stakeholder interviews and desktop research. The key grid infrastructure includes transmission and distribution lines as well as substations. Second, the peak loads of all five BET technologies at each charging hub for the pilot and scaled ZET deployment were estimated. The next step is to determine the number and sizes of new grid equipment required to meet truck charging power demand based on the remaining grid capacity and the peak load from charging. Finally, the aggregated cost figures are calculated based on equipment and labor cost data from DISCOM cost data books, tariff orders, and academic papers.

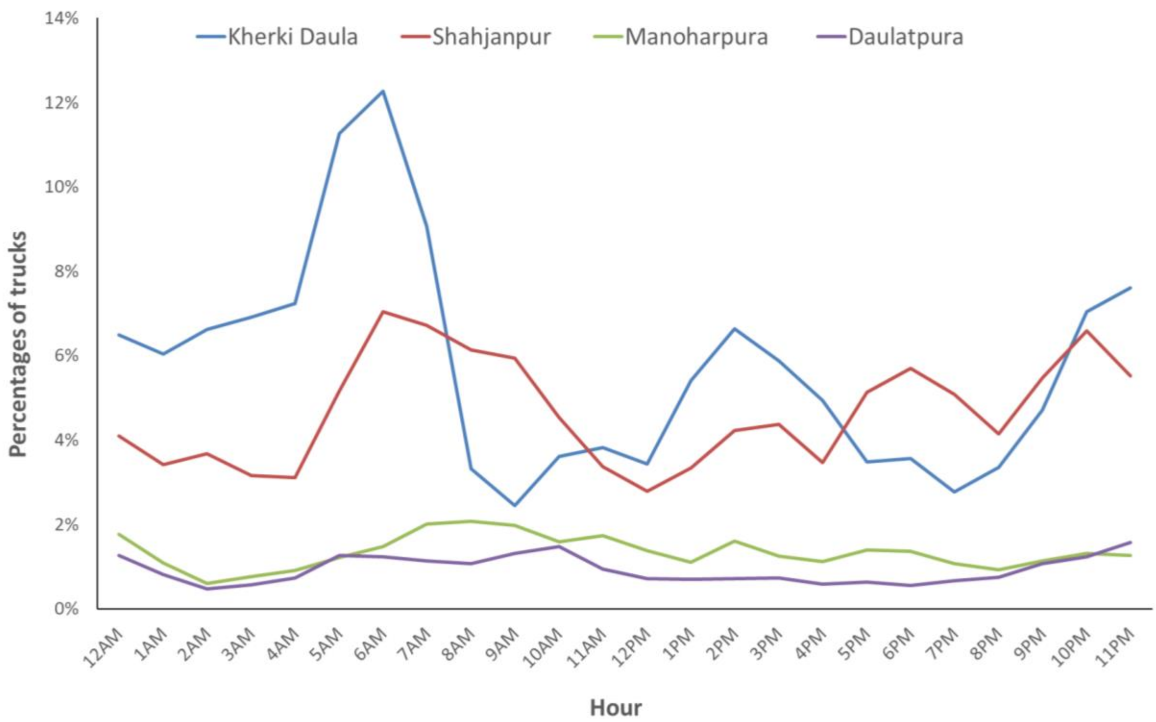
Figure 62: Grid cost assessment steps and method process



Step 1: Derive the hub location and spare capacity of existing grid infrastructure. Existing grid infrastructure mainly refers to transmission lines (220kV, 132kV) and distribution lines (66kV, 33kV, 11kV, 0.415kV), substations, and distribution transformers. According to the Open Infrastructure Map and interviews with stakeholders, there are six existing substations along NH-48 between Delhi and Jaipur, and the major transmission lines have approximately 100MW of spare capacity. On the distribution level, the spare capacities can support truck charging during the pilot stage but are insufficient for the scaled ZET deployment in 2030. Therefore, new distribution lines and transformers will be installed to step down the 220/132kV transmission-level voltages to charger-compatible voltages in the scaled deployment scenario.

Step 2: Peak loads of BET charging. Peak load events were designed based on the HDT truck charging demand, as the system needs to be designed to accommodate the highest demand. To estimate Peak loads this analysis derived truck traffic patterns from the IHMCL toll data. By assessing the hour and the percentage of truck traffic crossing the differing toll plazas along the Delhi-Jaipur corridor, this analysis assessed potential peak periods when an assumed maximum number of trucks would need to recharge. The figure below illustrates truck traffic passing through four toll plazas. Toll Plaza 1 and 2 consistently experience higher truck traffic compared to Toll Plaza 3 and 4. Notably, between Toll Plaza 1 and 2, there is a morning peak from 4 a.m. to 7 a.m. Throughout the rest of the day, both plazas exhibit similar traffic flows. Based on this data, the peak event was sized around the morning truck traffic and the expected charging needs in and around Delhi.

Figure 63: Percentage of traffic traveling along and between Delhi-Jaipur toll plazas



Peak traffic volumes are the primary design parameter when determining a technology's peak load. Therefore, changes in truck traffic would have a significant impact on load planning. Based on the available data, the following peak loads were calculated for each technology during both the pilot and scale-up phases. These peak loads were then utilized to size and estimate the level of grid upgrades required to accommodate truck charging.

Figure 64: Estimated peak loads for charging technologies

Peak loads in MW by hub	Swapping		Fast Charging		Ultra-Fast Charging		Catenary / Induction	
	Pilot: 2025	Scale: 2030	Pilot: 2025	Scale: 2030	Pilot: 2025	Scale: 2030	Pilot: 2025	Scale: 2030
Manesar Charging Hub		81		109.1		106.4		91.1
Bhiwadi Charging Hub	4.8	81	4.0	109.1	5.6	106.4	4.0	91.1
Neemrana Charging Hub	3.2	94.5	1.1	62.8	3.3	116.6	2.2	99.9
Kotputli Charging Hub		27		19.8		17.1		14.7
Shahpura Charging Hub		27		19.8		17.1		14.7
Jaipur Charging Hub	2.9	27	1.2	25.1	1.6	27.2	1.1	23.3

Note: In 2025, only the stations highlighted in blue will be utilized for the pilot. However, all stations will be utilized for scaled deployment in 2030

When comparing peak loads among the various hubs, it is noteworthy that Manesar, Bhiwadi, and Neemrana all experience higher peak loads than the other charging hubs upon scaled deployment in 2030. This is due to the greater share of truck mobility in and around this region, as indicated by toll traffic data. Therefore, it can be reasonably estimated that this increase in traffic activity would lead to more charging events taking place at these hubs.

The peak load was derived based on the number of assets at a station and the instance of all those being utilized at once. To derive the number of assets at a station this model seeks to derive behavior trends based on existing traffic data. However, operational patterns and these parameters of how and when people charge may evolve. The level of confidence in load spreading and behavior, particularly for fast charging, will be emergent. This model largely takes a conservative approach for peak loads, particularly for fast charging, and models a peak load instance in which all chargers are utilized at once. The reality is, there could be more or less strategic load spreading and peak load approximations may evolve with greater data granularity. Peak loads are also affected by factors such as traffic patterns and seasonal fluctuations. These variations may necessitate the installation of additional chargers to cater to increased demand during specific times. In such scenarios, the coincident peak could indeed become more pronounced, and the required grid upgrades would be more substantial.

Step 3: Sizing the equipment needed for grid upgrade. The equipment needed for grid upgrades can be determined based on the peak load and available spare capacities in the existing grid infrastructure. The key equipment required for grid upgrades includes distribution lines, substations, and transformers. Line costs are associated with the installation and connection of distribution lines to the six existing substations. Substation costs stem from the need for new distribution transformers to step down the voltage from 220kV and 132kV (at the transmission level) to 11kV and 33kV (at the charger level) at each charging hub. The size of the transformers and the voltage of the distribution lines are determined based on the charger voltage and the transmission level voltage. The connection and charger voltages and grid upgrade equipment of five BET technologies are summarized in Figure 63 below.

Figure 63: Sizing electrical equipment based on required power and power mechanics constraints

	Ultra-Fast Charging	Fast Charging	Swapping	Catenary	Induction
Transmission level connection voltage (kV)	220	220	132	220	220

Voltage (kV)	33 (Charger level)	11 (Charger level)	33 (Charger level)	1500 V wire	1500 V coil
Equipment needed	220/33kV substations; 33kv lines	220/11kV substations; 11kV lines	132/33kV substations; 33kV lines	220/1.5kV substations; 1.5kV lines	220/1.5kV substations; 1.5 kV lines

Step 4: Cost of grid equipment. The key grid infrastructure required in the grid upgrade process and their associated hardware costs are summarized in Figure 64 below.

Figure 64: Unit costs of key electrical infrastructure

Item	Cost (INR)	Source
220kV Line (per km)	1,15,00,000	DHBVN 22-23 Cost Databook
132kV Line (per km)	85,00,000	DHBVN 22-23 Cost Databook
66kV Line (per km)	75,00,000	Electric Vehicle Charging Infrastructure and its Grid Integration in India: Status Quo, Critical Analysis and Way Forward
33kV line (per km)	40,66,582	DHBVN 22-23 Cost Databook
11kV Line (per km)	6,62,297	DHBVN 22-23 Cost Databook
0.415 kV OH line with a bare conductor (per km) (3-phase, 4-wire)"	3,50,000	Electric Vehicle Charging Infrastructure and its Grid Integration in India: Status Quo, Critical Analysis and Way Forward
220/66/33/11 kV substation	67,70,73,000	DHBVN 22-23 Cost Databook
220/132/33 kV substation	51,89,89,000	DHBVN 22-23 Cost Databook
132/33 kV substation	20,03,93,000	DHBVN 22-23 Cost Databook
66/11kV substation	11,68,26,000	DHBVN 22-23 Cost Databook
11/0.415kV, 400kVA transformer	15,01,759	UP Electricity Regulatory Commission Cost Databook
Processing fee >10 MW	25,000	UP Electricity Regulatory Commission Cost Databook
Civil work for 33kV substation	1,41,52,777	DHBVN 22-23 Cost Databook

Only the hardware and labor costs are included in the analysis. These costs do not account for the cost of borrowing, as requisite grid upgrade costs are likely to be shared and allocated between various stakeholders. Maintenance costs are also excluded from the derived grid costs because they can vary significantly and depend on local conditions and the state of the grid infrastructure itself. Land costs were not included in the grid costs, as it was assumed that the land parcels of existing substations and transformers would provide adequate space for equipment additions.

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