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CHARGING SOLUTIONS FOR BATTERY-ELECTRIC TRUCKS

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EXECUTIVE SUMMARY

The battery-electric truck market is at an early stage, with fewer than 60,000 units in circulation worldwide, including approximately 20,000 units sold in 2021. Ninety percent of these were sold in China, and most were on the lighter side of the category, between 3.5 and 8 tons. However, significant growth in the market is expected in the coming years as more governments and truck manufacturers set combustion engine truck sales phase-out targets, more models become available, and production capacity is increased. A robust charging infrastructure ecosystem, along with sufficient grid capacity, must be deployed early enough not to impede the growth of the electric vehicle fleet.

This paper provides an overview of charging solutions for battery-electric trucks, their cost, and timeline for implementation. Additionally, electricity demand and grid impacts are estimated in two case studies of Germany and the United States, emphasizing the need for upfront planning and grid upgrades, and the potential of smart charging. Finally, the paper catalogs and synthesizes lessons from policies and pilot programs across China, Europe, and North America. The research leads to the following findings:

Early electric trucks have relied on charging infrastructure designed for light-duty vehicles, but more powerful standards are ready for commercialization and will unlock new applications. Wired stationary charging options range from AC slow with power below 43 kilowatts (kW) to DC fast charging with power up to 350 kW. Higher power standards are under development—ChaoJi in China will deliver up to 900 kW and CharIN MegaWatt Charging System in Europe and North America could deliver up to 3.75 megawatts (MW). There are currently multiple charging standards in use. Harmonization of hardware and software standards is key to enabling economies of scale, reducing development costs for both truck and charger manufacturers, ensuring interoperability, and ensuring that an international used zero-emission vehicle market can flourish.

Wired stationary charging is the dominant technology, but novel alternatives are being tested to increase charging flexibility. Wired stationary chargers can be classified by their use purpose: overnight charging at a private depot or public in rest areas along highways (up to 100kW), opportunity fast charging at destinations or along highways (up to 350 kW), and opportunity ultra-fast public charging (above 1MW). There is no one-size-fits-all for the ideal mix of charging options, as it depends on fleet size, daily mileage, type of operation, and fleet managers' strategies. Battery swapping, overhead catenary charging, and in-road wireless charging are three emerging alternatives to standard wired charging. These three technologies could reduce battery-electric truck charging downtime and reduce upfront truck costs and weight by enabling reduced battery sizes. However, political and business challenges impact the deployment of these technologies.

Advanced planning and grid management are key to managing electricity demand in a time- and cost-efficient way. Grid upgrades add significant cost and time constraints to the uptake of battery-electric trucks, making advanced planning and grid management strategies key. Two case studies on Germany and the United States were conducted to assess energy, charging infrastructure, and power output needs up to 2040. The results show that in 2040, battery-electric truck energy needs will represent 6% and 3% of Germany's and U.S.'s 2021 electricity production, respectively. This does not necessarily imply that a 6% and 3% increase in grid capacity will be needed, since the existing infrastructure can be leveraged through demand management and minor distribution network upgrades. The grid impacts of electric trucks can be managed through a revision of public electric utility business models, coordinated planning between relevant stakeholders, and the implementation of smart charging solutions.

To ensure that infrastructure is built alongside truck deployment at a reasonable cost, regulations should set targets for charging infrastructure deployment and regulations on the power sector should be updated. The European Union was the first jurisdiction to propose regulations setting the pace of charging infrastructure roll-out for heavy-duty vehicles. These regulations include traffic-based targets for the placement and power output of charging hubs. To ensure upgrades to the electricity grid, the California Public Utilities Commission approved a new tariff bill in 2021 which makes investor-owned electric utilities responsible for the build-out of grid infrastructure, such as distribution lines, transformers, trenching, and construction. A similar regulation is in place in China, where the two state-owned grid companies are responsible for helping station operators access the grid and the related cost. Coordination between multiple government agencies, electricity utilities, and commercial fleets is key for a successful transition to electric vehicles.

In the early stages of charging infrastructure buildout, direct support through pilot projects and financial incentives can build confidence and scale. Most jurisdictions offer funding for battery-electric truck charging infrastructure to assist with research and innovation, purchase and installation, and connection to the grid. These funding programs should include equity considerations to ensure that small charging station and truck operators have adequate access. In addition to financial incentives, several pilot projects are also underway to test emerging technologies such as a megawatt charging system trial in Germany, a catenary charging pilot project in the United Kingdom, battery swapping pilots for trucks in several cities in China, and smart charging projects for battery-electric truck fleets in California. While pilot projects are helpful to assess emerging technologies, work on the grid should begin immediately since grid upgrades and implementation of mitigation strategies will be needed independent of the technological charging solution.

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INTRODUCTION

Global sales of medium- and heavy-duty battery-electric trucks increased between 2020 and 2021 after decreasing for several years. Battery-electric truck sales have largely been driven by the Chinese market; China accounted for 91% of the worldwide battery-electric truck sales in 2021, which amounted to more than 18,000 units. Europe is the second-largest market with around 1,500 units sold in 2021.

Even though the battery-electric truck market is still nascent, with about 0.1% of trucks being battery-electric, it is expected to grow significantly in the coming years. Indeed, several governments and truck manufacturers have announced intentions to phase out sales of internal combustion engine trucks (ICCT, 2022). Sixteen national governments and 50 sub-national governments and private sector stakeholders have signed a Global Memorandum of Understanding on zero-emission medium- and heavy-duty vehicles (Drive to Zero, 2021). Under this memorandum, sixteen countries—Austria, Canada, Chile, Denmark, Finland, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Scotland, Switzerland, Turkey, the United Kingdom, Uruguay, and Wales—commit to working together to enable 100% zero-emission new truck and bus sales by 2040, with an interim goal of 30% zero-emission vehicle sales by 2030, to achieve of net-zero carbon emissions by 2050.

In addition to this memorandum, Norway has a target of 50% zero-emission truck sales in 2030 and Chile has a target of 100% new medium- and heavy-duty trucks being zero emission in 2045. Seventeen U.S. States, the District of Columbia, and Québec (Canada) released an action plan to rapidly advance electric truck and bus adoption (NESCAUM, 2022), and six of them have adopted California's Advanced Clean Trucks rule (CARB, n.d.), which requires an increasing number of zero-emission trucks to be sold by manufacturers. Manufacturers must increase their zero-emission rigid truck (Class 4–8) sales in those states to between 30% and 50% by 2030, and between 40% and 75% by 2035. Austria, California, and Cape Verde have also set targets for full truck fleet electrification by 2035, 2045, and 2050, respectively. On the manufacturing side, Mercedes/Daimler and Scania have announced the targets of hitting 100% zero-emission truck sales in Europe by 2039 and 2040, respectively.

The lack of robust charging infrastructure system could jeopardize a jurisdictions' ability to keep up with their zero-emission truck goals. Addressing this barrier would unlock large environmental and social-economic benefits. This paper assesses the current state of charging solutions for battery-electric trucks to inform key policies needed to foster infrastructure deployment in a time and cost-efficient manner. Specifically, it provides an overview of different charging technologies available for battery-electric trucks, assesses future electricity demand and the impact on the grid, considers policies and programs implemented to date in China, North America, and Europe to support battery-electric trucks, and highlights remaining challenges and barriers to charging infrastructure deployment.

In this report, charging infrastructure includes all devices allowing the recharging of an electric truck. This includes wired stationary charging, battery swapping, overhead catenary charging, and wireless in-road charging. A charger is defined as the device through which the electric vehicle receives electricity, while a station is an agglomeration of chargers at a similar location. While hydrogen may also play a role in decarbonizing the commercial truck sector, hydrogen refueling is not considered in this report given the large differences in technology and slower pace of market growth through 2022.

OVERVIEW OF CHARGING TECHNOLOGIES

Millions of stationary wired chargers have been built for electric cars around the world. Similar technologies are also being developed for battery-electric trucks. This section provides detailed information on wired stationary charging types, cost estimates, and installation timelines. It also reviews emerging charging technologies, including battery swapping, overhead catenary charging, and wireless in-road charging.

WIRED STATIONARY CHARGING

Charger type and location

There are different options for the wired stationary charging infrastructure to meet the varying needs of battery-electric trucks, including fleet size, daily mileage, and type of operation. These options range from slow alternating current (AC) charging with power below 43 kilowatts (kW) to fast and ultra-fast direct current (DC) fast charging with power up to multiple MW (in development). The typical location of these chargers varies. Depot charging is located at an operator's terminal and is normally used for overnight charging. Destination charging is used by trucks while loading and unloading at locations such as retail locations, distribution centers, and multi-modal terminals such as ports. Public charging can be used during the day or night at publicly accessible locations. The most common charging types, their typical locations, and estimated charging times are presented in Table 1 below.

Table 1. Summary of wired stationary charging types

Charger type	Nominal power output	Charging standard	Location	Estimated charging times
Overnight	50–150 kW DC	Combined Charging System (CCS) or CHAdeMO	Depot, public parking space	8 hours
Opportunity fast	150–350 kW DC		Public charging station, depot, destination location	0.5 hours
Opportunity ultra-fast	750 kW–3 MW DC	Megawatt Charging System (MCS) or ChaoJI	Public charging station, depot, destination location	0.5 hours

While typical opportunity charging times of 30 minutes may not seem realistic during the workday, it is important to note that there are regulations imposing breaks on truck drivers. For example, in the EU, truck drivers must take a 45-minute break every 4.5 hours, which is enough time for a top-off during the day.

Standardization of both hardware and software is key to enabling economies of scale, reducing development costs for both truck and charger manufacturers, ensuring interoperability, and ensuring that an international used ZEV market can flourish. Similar to the light-duty vehicle sector, there is currently a variety of charging standards, with CHAdeMO/ChaoJI mainly deployed in Asia and CharIN primarily used Europe and North America. Other countries are still deciding on which standards to adopt (Pettigrew & Vera, in press). Table 2 below summarizes the high-power standards in development.

Table 2. High-power standards in development

Standard name	Organization(s) in charge	Market	Max voltage and amperage	Maximum power	Timeline	Compatibility
ChaoJi	China Electricity Council and CHAdeMO	First used in China and Japan	1,500V and 600A	900 kW		Backward compatibility with all current global standards.
MegaWatt Charging system (MCS) CharIN	Industry Task Force set up by CharIN	Europe and North America	1,250V and 3,000A	3.75 MW	Pilot projects in 2023, planned commercialization in 2024.	Compatible with the CCS infrastructure.

Charger cost

The different charging types listed above vary widely in terms of their total cost. There are three main factors affecting cost: rated power output, location (depot, private destination, public), and number of charging points per station. The total cost of charging infrastructure includes upfront and operating costs. The upfront costs include the station's hardware and software, the electric utility connection, the construction permit, and planning and installation costs. Operating costs include maintenance, electricity, and back-end telecommunications and management. The cost of land can fall under both the upfront and operational cost categories, depending on whether the land is owned or rented. Similarly, potential grid upgrade costs can fall under upfront costs or operational costs if electric utilities distribute the costs for these upgrades over time, such as in the form of a surcharge in the contracted rate design.

Table 3 below provides estimates for the cost breakdown as of 2022 for four different speeds of public chargers, based on data from Nicholas & Wappelhorst (2022) and European Commission (2021). Agora Verkehrswende have found similar cost estimates (Meyer, 2022). These costs are based on European data and can vary greatly between jurisdictions. For the grid connection, planning, and installation costs, we spread the cost among four chargers, assuming an average of four chargers per station. Operation and maintenance costs are estimated as a fraction of capital costs per year. The costs presented above do not include subsidies, and inflation and the rising price of materials has not been taken into account. Learning rates and economies of scale can be assumed to reduce hardware and software, planning, and installation costs by around 2% per year.

Table 3. 2022 cost estimates for four different speeds of public chargers

Public charger power	Hardware and software	Planning	Installation	Total upfront costs (hardware and software, planning, and installation)	Operation and maintenance per year
Public 50 kW DC	€28,125	€1,350	€15,200	€44,700	1.2%*28,125 = €340/year
Public 150 kW DC	€70,000	€3,645	€18,000	€91,700	1.2%*70,000 = €840/year
Public 350 kW DC	€170,000	€7,655	€54,000	€231,700	1.2%*170,000 = €2,040/year
Public 1 MW DC	€440,000	€21,800	€154,000	€615,800	1.2%*440,000 = €5,300/year

Grid upgrade cost and timeline

The potential electricity grid upgrade costs are not included in the previous table as they can vary significantly depending on the project and location. The infrastructure to be upgraded by public electric utilities can include distribution lines, local stations, breakers, transformers, and switchgears. Electricity grid upgrades are necessary where on-site power availability is not sufficient. Grid upgrades can range from minor, such as only upgrading the breaker and distribution transformer, to major upgrades of the distribution lines and substation. Note that not all these costs will be borne by the company needing the upgrade. At a higher level, this is financed by electricity utilities who might earn back this money through general grid tariffs.

In 2019, the Netherlands government published an overview of grid upgrade cost and time for cables and substations, ranging from low voltage (around 150 kW) to extra-high voltage (greater than 500MW) (Netbeheer Nederland, 2019). The costs are summarized in Table 4 and Table 5.

Table 4. Example of connection cost in space, time, and money for cables in the Netherlands

Cable type	Width of the space needed	Lead time	Costs in €/meter
Extra high / high voltage line (>500MW)	100 m	7–10 years	5,000–10,000
High voltage cable (100 – 300 MW)	10 m	5–7 years	1,000–5,000
Intermediate Voltage cable (100 – 300 MW)	10 m	1–3 years	300–1,000
Medium Voltage cable (20 – 100 MW)	1–10 m	0.5–3 years	100–400
Low voltage cable	1 m	0.5–1 year	70–150

Table 5. Example of connection cost in space, time, and money for substations in the Netherlands

Station type	Space needed	Lead time	Cost in €
Extra high to high voltage stations (>500MW)	40,000- 100,000 m^2	7–10 years	> 100,000.000
High to Intermediate voltage station (100 – 300 MW)	15,000 – 45,000 m^2	5–7 years	> 25,000,000
High to Medium voltage station (100 – 300 MW)	15,000 – 40,000 m^2	5–7 years	> 25,000,000
Intermediate to Medium Voltage station (20 – 100 MW)	2,000 – 10,000 m^2	2.5–5 years	1,500,000–10,000,000
Medium voltage station (10 – 40 MW)	200 – 4,000 m^2	2.5–3 years	1,300,000–6,500,000
Medium to Low voltage station (0.2 – 1 MW)	10 – 35 m^2	0.5–1 year	35,000–250,000

Charger implementation time

Beyond cost, time can considerably impact a charging infrastructure deployment project. Currently, the process is relatively time-consuming depending on local regulations, administrative times, and grid upgrade times. The time from the beginning of the planning process to the entry into service of the station can also vary widely. Depending on projects and local conditions, it can take more time to get a charger up and running than to purchase a battery-electric truck fleet, thus planning ahead is key.

The California utility Pacific Gas and Electric estimates a charging station installation project for electric vehicle fleets to take between nine and 13 months (California utility Pacific Gas and Electric, n.d.). When transmission grid updates are needed the timeline can be considerably longer—up to 10 years according to a study conducted in Norway (Brembu, 2022). Because much of this time is spent on planning and permitting, it is paramount that the process starts long before charging needs arise.

Summary

Table 6 summarizes wired stationary charging options for battery-electric trucks, including charger type, typical location, estimated capital cost, and use type.

Table 6. Summary of battery-electric truck wired stationary charging options

Public or private	Location and type	Power output	Estimated upfront cost of charger in 2022	Use type
Private	Depot	50 kW DC	€44,700	Fleet returning to same location every night Small-medium size batteries
		100–150 kW DC	€91,700	Fleet returning to same location every night Small-medium size batteries
	Destination opportunity	350 kW DC	€231,700	Fleet idling for at least 45 min-1hr when loading and/or unloading goods
Public	Overnight	100–150 kW DC	€91,700	Fleet not returning to the same location every night
	En-route and destination fast	350 kW DC	€231,700	High mileage/heavily loaded fleets not returning to the same location every night 3-4 hours rest during the day.
	En-route and destination ultra-fast	1 MW DC	Unknown, as technology is not yet deployed. Estimates for 1 MW chargers are around € 615,000.	High mileage/heavily loaded fleets not returning to the same location every night
		3 MW DC		Large batteries, needing a quick top-up during the day, 45 minutes rest.

Note: Estimated upfront cost includes hardware and software, planning, and installation.

The table above provides estimates for typical commercial truck use cases, but the flexibility of charging technology enables different manufacturers and fleets to adopt different strategies optimized for their own use cases. There is no one-size-fits-all for the type of chargers to be used by certain fleets. The relative importance of different charger types and charging locations will depend on factors such as technology availability and fleet operator preferences. Fleet operators' decisions regarding charging installation is often heavily weighted by the total cost of ownership, which depends on regional parameters such as electricity prices.

EMERGING ALTERNATIVE CHARGING SOLUTIONS

Battery swapping

Compared with wired stationary charging, battery swapping technology could significantly shorten the time required to recharge electric vehicles. This option can be appealing for truck owners, as they have low tolerance for long charging times from a economic perspective. Nonetheless, there are some key barriers that need to be overcome to commercialize battery swapping, such as the lack of standardization of batteries and the high capital cost of battery swapping stations. Currently, batteries used by different companies vary by shape and size and are placed in the truck in different ways. Thus, drivers of trucks that enable battery swapping usually could only use specific battery swapping stations. Recent data in China shows that the capital cost of a typical battery swapping station for heavy-duty trucks is over ¥10 million (~ US$1.5 million), much higher than a charging station with similar service capacity (Zhou, 2022). Based on data from multiple Chinese operators, batteries usually account for 30% to 40% of the total capital cost of a battery swapping station, which increases with the battery capacities of the station (CATARC, 2021).

In recent years, China has been at the forefront of promoting battery swapping technology. In China, battery swapping is typically offered under a battery-as-a-service (BaaS) business model. Fleet owners only pay for the vehicle body (without batteries) when they purchase electric trucks, which results in a reduction of upfront cost, and battery swapping station operators purchase and provide fleet owners with access to fully charged batteries. By the end of 2021, China had built at least 1,298 battery swapping stations, although most of which are used to serve electric passenger vehicles, including taxis and private cars (STDaily, 2022).

Battery swapping applications for heavy-duty trucks are at an earlier stage. Key market players in China include truck manufacturers such as Sany Heavy Truck and Geely Commercial Vehicle, battery suppliers such as CATL, and grid companies such as the State Power Investment Corporation (SPIC). For example, SPIC has already built more than 100 battery swapping stations and deployed more than 10,000 battery-swapping-enabled heavy-duty trucks as of early 2022, and plans to deploy 200,000 heavy-duty trucks and own 4,000 battery swapping stations by 2025 (EVPartner, 2022). Beijing pioneered the use of battery-swapping-enabled heavy-duty trucks for the shipping of raw gravel from mining sites located on the outskirts of Beijing to concrete plants in the city. These trucks featured a battery capacity of 282 kWh, an electric range of 170 km and a battery swapping time of 3 minutes (Han et al., 2021). By mid 2021, 111 battery-swapping-enabled heavy-duty trucks had been deployed in Beijing, which had shipped raw gravel over 5 million km (Li, 2021).

The Chinese central government has expressed clear support for battery swapping-enabled heavy-duty trucks for short-haul applications at ports, mining sites, and in urban logistics (NDRC, 2021). In October 2021, China launched a two-year pilot program to promote the application of battery swapping technology. Among the 11 pilot cities selected, three are expected to fully focus on heavy-duty truck application while the others are expected to demonstrate this new technology on both heavy-duty trucks and passenger vehicles (MIIT, 2021). The pilot program is described in more detail in the China policy section of this paper.

Outside of China, there have been few experiments with battery swapping technology. As a result of high capital cost and low consumer demand, early commercial attempts to promote battery swapping by Better Place and Tesla did not achieve success. Subsequently, discussions on battery swapping faded in Europe and the United States. India is considering promoting battery swapping technology, but mainly for two and three wheelers (NITI Aayog, 2022).

Overhead catenary charging

Overhead catenary charging allows trucks to charge while driving with electricity flowing through a pantograph connected to an overhead contact line. This technology is complementary to wired stationary charging technology, as the goal is not to electrify the entire road network. Catenary charging combines the advantage of efficient energy supply via catenary wires while driving on main roads (primarily highways), lower upfront investment costs for truck companies due to smaller batteries, and reduced downtime from charging. It also leverages the extensive experience and economies of scale of building pantographs and overhead lines for electrified trains, trams, and trolley buses. Overhead lines can be also constructed without significantly interrupting traffic on the highway, in contrast to in-road wireless charging. With this technology, there is a compromise to find between the number and location of kilometers electrified with catenary charging and the truck's battery size.

Although overhead catenary makes sense technology-wise, there are political and business barriers. It is important to note that this technology shifts some of the costs away from the vehicle owner due to the smaller battery sizes required and the public nature of the charging infrastructure. However, this means that more public funds might be needed in the beginning and the decision about who will own and pay for the infrastructure in the long run is unclear. Additionally, for wide scale development, international standards are key to making cross-border travel possible, especially in Europe.

As of 2022, this technology is still at an early stage; however, several pilot projects have already been conducted, mostly in Europe and North America. Siemens has deployed catenary charging in Sweden, Germany, and California, and has undertaken a feasibility study of this technology in the UK. Electrifying 1 km of highway in Germany is estimated to cost approximately €2.5 million, with a target of €1 million at scale (Siemens, 2022). To sustain long-haul transport in Germany, approximately 4,000 km of highway would need to be electrified, amounting to €10 billion (Öko-Institut e.V., 2020). Dutch studies estimate these costs to be closer to €3–€3.5 million per electrified kilometer (Rijksoverheid, 2021; Rijksoverheid, 2022).

A study published in 2020 by the Centre for Sustainable Road Freight assessed the potential of using this technology in the UK (Ainalis D.T. et al., July 2020). The study showed that building a network of overhead catenary cables along 7,500 km of the UK's major road network would electrify approximately 65% of kilometers traveled by heavy good vehicles at an estimated cost of £19.3b and could be achieved by the late 2030s. This study also demonstrated that investments would be paid back in 18 months for vehicle owners through lower energy costs and in 15 years for catenary line infrastructure investors through electricity sales profit margins.

The cost competitiveness of overhead catenary charging compared to wired stationary charging depends on the required grid upgrade cost. These costs are dependent on the specific projects and local conditions.

Wireless in-road charging

Wireless in-road charging works by transferring electricity from magnetic coils embedded in the road to receiving coils fitted to electric vehicles. Like overhead catenary charging, it allows electric trucks to charge while driving. Thus, this technology has the potential to reduce range anxiety and lower the upfront cost of owning an electric truck by reducing battery size. In addition, wireless in-road charging has one key advantage over overhead catenary charging: it can be used by both trucks and cars, which increases the use case.

However, wireless in-road charging for electric trucks is associated with several major challenges, in addition to the technical complexity of sending and receiving large amounts of energies while the vehicle is driving. The first challenge is the high cost to set up electrified roads and the corresponding political and business barriers, much like those for overhead catenary charging. Public data indicates that the cost of a wireless charging road is around USD 1.2 million per km (Houser, 2018). Second, to ensure interoperability of vehicle brands and charging suppliers, technical standardization and unification of operational standards is needed. Third, the impacts of radiation from high-energy wireless charging on humans and animals is currently unclear (Liu et al., 2021). The forth challenge, especially for tractor-trailers, is the limited space on tractors to install coils that could receive enough inductive power needed to drive trucks with large gross vehicle weight rating.

Because these major challenges are to date unaddressed, wireless in-road charging is still at a very early demonstration stage and is not in commercial use. Only a few pilot programs have been launched in a limited number of countries, such as Sweden and the United States (Smart City Sweden, 2022; Mott, 2022). In addition to wireless in-road charging, wireless depot charging is also gaining interests in the United States. Antelope Valley Transit Authority (AVTA) in Southern California has deployed three wireless charging pads in each of their four transit centers throughout their bus routes, with charging power of up to 250 kW (Royal, 2022).

ENERGY AND POWER DEMANDS: UNDERSTANDING POTENTIAL IMPACTS ON THE GRID

This section aims to provide insights on energy and power requirements, as well as associated costs of infrastructure, that are needed to electrify truck fleets, using the German and U.S. markets as examples. It also discusses the impacts of battery-electric trucks on the grid based on a literature review.

MODELLING CHARGING INFRASTRUCTURE NEEDS FOR BATTERY-ELECTRIC TRUCKS

Through a modeling analysis, we first estimate the energy demand for battery-electric trucks for the German and U.S. markets for the period 2021 to 2040. We then model the number of chargers required and the associated costs.

Scenario descriptions

The case study for Germany builds upon the Manufacturer Aligned Zero Emission Targets scenario developed by the ICCT (Mulholland et al. 2022). This scenario uses the ambitions stated by European manufacturers for fossil-free truck sales share targets between 2025 and 2040 as its basis. The different ambitions of manufacturers are weighted across their sales share. Aligning the European CO_2 regulation with the ambition showcased by manufacturers would lead to a new ZEV sales share of around 40% in 2030, and a full phase-out of combustion heavy-duty engine sales in 2040.

For the U.S. case study, zero-emission truck deployment projections assume that the 2035 zero-emission sales targets formulated under California's Advanced Clean Truck (ACT) regulation are achieved nationwide, which therefore represents an ambitious case study. The ACT zero-emission sales shares for 2035 are 55% for Class 2b-3 truck sales, 75% for Class 4-8 straight truck sales, and 40% of truck tractor sales.

This scenario is further described under Alternative 2 designed by ICCT, 2022, where ZEV sale shares increase linearly to 100% by 2040 after the ACT requirements end in 2035 for rigid trucks and after 2032 for tractors (California Air Resources Board, 2021; International Council on Clean Transportation, 2022).

Key Assumptions

The level of infrastructure rollout required to support the transition to battery-electric trucks largely depend on real-world truck activity and charging strategies adopted by fleets. This is expected to significantly vary across jurisdictions, industry sectors, and vehicle types. As the market is still nascent and little data exists to inform those inputs, we develop assumptions on what we estimate to be the most representative truck activity and charging strategy for each truck segment, in each jurisdiction. The key assumptions influencing our modelling results are described below.

First, the distance traveled by each vehicle segment is a key determinant of energy demand from the fleet, and therefore the level of infrastructure required. We model the daily vehicle kilometers traveled (VKTs) through a parametrized lognormal probability function, based on real-world data. The level of activity impacts both the installed power required and the relative dependence on different charger types.

Second, fleet operators can opt for different charging strategies. Cost and use differ significantly across different charger types. For example, a fast charger at a public charging station on a busy highway is expected to be more heavily used than a public overnight charger at a remote location. Therefore, different charging strategies can lead to significantly different levels of infrastructure deployment and investments. Here, we assume that most vehicle fleets prioritize overnight depot charging, as it is the most cost-effective charging strategy. We assume that only long-haul trucks will require public overnight chargers, while all other trucks will charge overnight at private depots. The portion of daily energy needs that cannot be satisfied by overnight charging will be covered by opportunity fast (350 kW) and ultra-fast (1 MW) charging. The full methodology is described in Minjares et al. (2021).

Finally, the time windows available for charging are key in determining the level of infrastructure required. We assume 8 hours are available for overnight charging events, and 30 minutes are available for fast charging events.

ENERGY DEMAND AND INFRASTRUCTURE COSTS

For Germany, we estimate energy demand from battery-electric trucks to be 13 TWh in 2030, or the equivalent of about 1% of the total electricity produced in Germany in 2021. The energy demand from battery-electric trucks then increases to about 120 TWh in 2040, the equivalent to 6% of the total electricity produced in 2021 (Bundesverband der Energie- und Wasserwirtschaft, 2021).

We estimate energy demand from battery-electric trucks in the U.S market to be 39 TWh in 2030, or the equivalent of less than 1% of the total electricity produced in the country in 2021. Battery-electric trucks' energy demand then increases to about 254 TWh in 2040, the equivalent to 3% of the total electricity produced in 2021 (Energy Information Administration, 2022a).

Figure 1 shows the number of overnight depots and public chargers, as well as the number of fast and ultra-fast chargers, needed to sustain the growth of the battery-electric truck fleet in the German and in the U.S. markets.

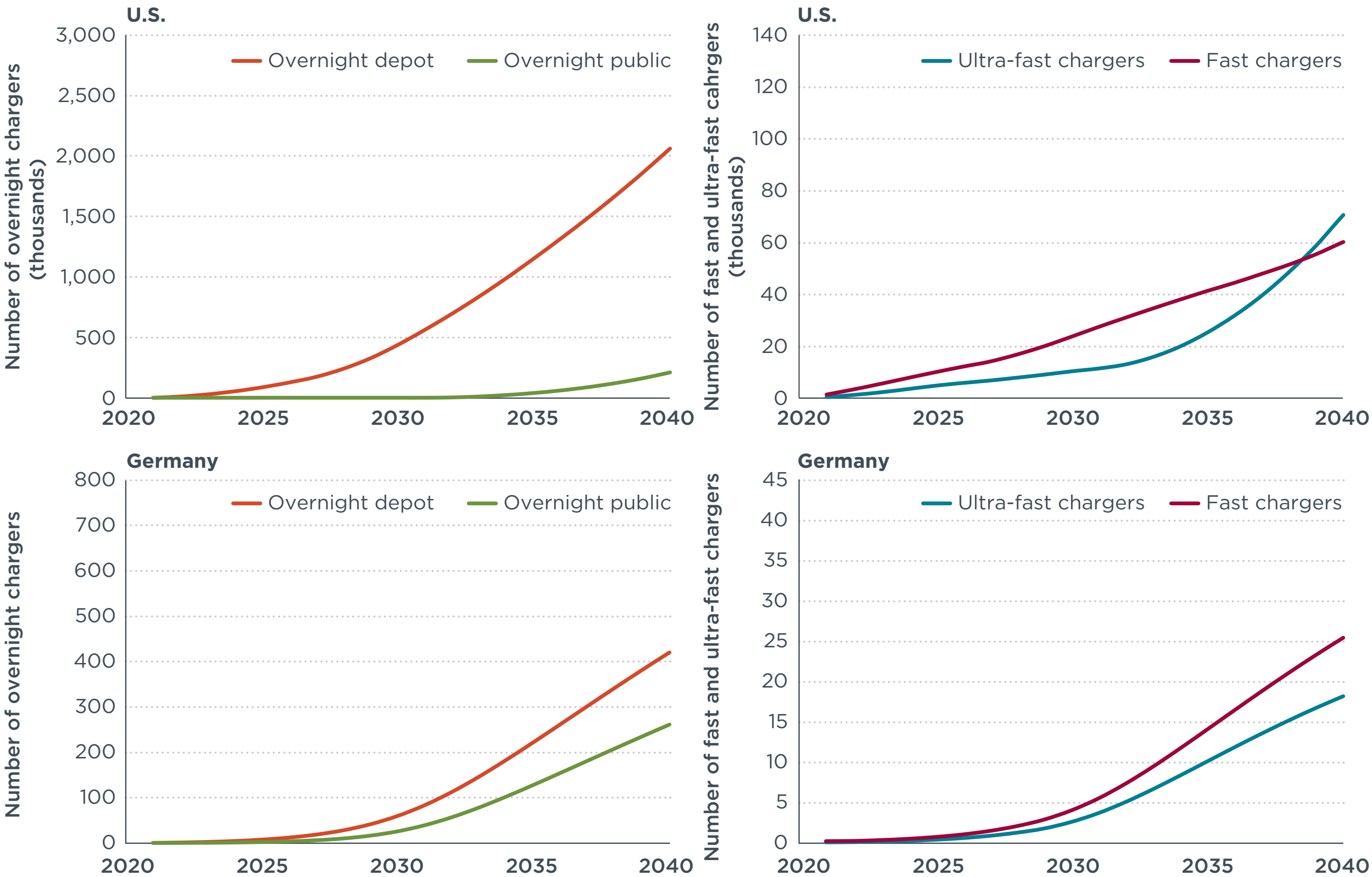

Figure 1. Number of chargers, per charger type, needed to sustain the growth of the battery-electric truck fleet in Germany and the United States

By 2040, the estimated 1.2 million battery-electric trucks operating on German roads will require approximately 715,000 chargers, with 59% being overnight private depot charging, 35% being publicly accessible overnight charging, and 6% providing fast and ultra-fast charging services (350 kW and 1 MW). We estimate a total cumulative investment of about €46 billion will be needed (covering hardware, construction, and installation costs) to deploy the charging infrastructure required to accommodate the growing battery-electric truck fleet up to 2040. A significative share of this investment is expected to come from the private sector.

Similarly, in the U.S. market by 2040, an estimated fleet of 4.7 million battery-electric trucks will require approximately 2.3 million chargers, with 91% being overnight private depot charging, 3% being publicly accessible depot charging, and 6% proving fast and ultra-fast charging services. Our model estimates that total cumulative investments of €153 billion ($155 billion) will be needed to deploy the charging infrastructure required to accommodate the growing battery-electric truck fleet up to 2040. As stated above, similar as for light-duty vehicles, charging deployment might first rely heavily on public subsidies but, in the long run, most of the investment will come from the private sector.

We expect that by 2040, Germany will rely on a much higher share of public overnight chargers, as we model a higher share of battery-electric long-haul trucks than in the United States, where the trucks will more heavily rely on depot charging. Hence, the composition of the truck fleet in each jurisdiction largely influences the needs for different types of chargers.

BATTERY-ELECTRIC TRUCK POWER DEMAND AND IMPACTS ON THE GRID

Due to their larger batteries, electric trucks are expected to have greater charging power demand compared to light-duty electric vehicles. The total rated power capacity of all charging stations in the analysis above would amount to 12 GW in Germany and 63 GW in the U.S. by 2030. The amount of power which would be consumed for charging electric trucks at any one time is considerably smaller because not all battery-electric fleets will charge simultaneously at maximum power. This is equivalent to about 5% of the total 2021 installed capacity in both markets (Energy Information Administration, 2022b; Energy Charts, 2022). By 2040, the total rated power capacity of all charging stations will increase to 94 GW for Germany and 305 GW for the United States, equivalent to about 41% and 27% of the total installed capacity in 2021, respectively.

The significant power demand required for battery-electric trucks leads to concerns regarding if the electricity grid will be able to cope with the increasing electricity load. While electric trucks have higher power requirements compared to light-duty vehicles, there has been limited research that has focused specifically on the impact of battery-electric trucks on the grid. Other recent studies have either focused on electric buses or electric vehicles in general (including a mix of all segments). Table 7 summarizes the key findings and assumptions of the most recent literature review on this topic as of mid-2022.

Table 7. Summary of findings from the literature review on electric vehicles' impact on the electricity grid

Study	Location	Key assumptions	Key findings

Borlaug et al. (2021)	Texas, United States	• Fleet: Drayage truck vehicles
		• Charging Strategy: overnight depot.
		• Three charging scenarios are studied:
		  • "100kW immediate" uncoordinated charging
		  • "100 kW delayed" allow postponed charging
		  • "Constant minimum power" fleets charge during off-shift periods at minimum power
		• Two EV loads are modeled:
		  • Low: 10 EVs
		  • High: 100 EVs
			• When charging 10 EVs at 100 kW, about 94% of the 36-substation modelled do not require upgrades during peak day profile in the immediate and delayed scenarios. This increases to 94%–97 % when the fleet is allowed to charge at minimum power,
			• When charging 100 EVs at 100 kW about 78%–86% of the substations can satisfy the demand without any upgrades in the immediate and delayed scenarios. This increases to 89%–92 % when the fleet is allowed to charge at minimum power

El Helou et al. (2022)	Texas, United States	• Fleet: Heavy-duty vehicles (Class 7, 8, and 9) > 26,000 lbs.
		• Charging strategy: Not specified
		• Charging scenarios:
		  • 17,000 electric buses charging simultaneously at a few locations
		  • 38,000 buses charging simultaneously at a few locations
			• About 17,000 buses (about 6% of Texas heavy-duty vehicles fleet) already causes non negligible voltage violations on the transmission grid when charging simultaneously
			• 30,000 buses (about 11% of Texas heavy-duty vehicles fleet) would cause severe voltage violation on the transmissions grid when charging simultaneously
			• Smarter distribution of charging event among feeders can help mitigate the impact of electric buses on the transmission grid. This, however, requires effective planning between utilities and the transport sector

Zhu et al. (2020)	California, United States	• Fleet: Heavy-duty vehicle (long-haul trucks) • Charging strategy: Exclusive use of fast charging stations • Two different distribution systems are studied: The IEEE 34-bus system and a realistic feeder from California • Each distribution system includes three scenarios: "good location," "mediocre location," and "worse location."	• The analysis conducted under the IEEE 34-bus system found that the grid counts fewer voltage violations under the "good location" scenario, and therefore accommodate best heavy-duty vehicles. • Similar results were found under the realistic California feeder, where the "good location" scenario showed the best ability to accommodate long-haul trucks Furthermore, the analysis investigated integrating smart chargers and find that they further help in limiting voltage variations.

Bermejo et al. (2021)	Germany	• Fleet: Passenger cars, commercial vehicles, trucks, and buses
		• Charging strategy: Heavy-duty trucks charge at fleet hubs
		• Two EV project scenarios are studied:
		  • Base case scenario: 8 million EVs will be circulating on the German roads by 2030
		  • Aggressive scenario: 16 million EVs will be on the roads by 2030
		• Two charging scenarios are analyzed:
		  • The unmanaged charging scenario, where charging events do not follow any specific planning/coordination
		  • The managed scenario, where charging events are coordinated to minimize peak demand
			• In an unmanaged charging scenario, the study found that as the number of EVs on the road increases, the main infrastructure that requires upgrades are the residential transformers.
			• Under the managed scenario, however, the model shows that strategies that encourage off peak hours charging considerably mitigated impact on the grid, flattening the peak load by 80%. These strategies include price schemes for specific time-of-use charging or vehicle-to-grid discharging during peak hours

Study	Location	Key assumptions	Key findings

Al-Saadi et al. (2021)	Jaworzno, Poland	• Fleet: Heavy-duty buses
		• Charging strategy: Overnight at depots or en-route via a pantograph.
		• Two scenarios:
		  • "Uncoordinated charging": e-buses charge until full maximum power allowed, without considering the number of buses that are simultaneously connected to the grid.
		  • "Coordinated charging": smart charging technologies are used to minimize simultaneously charging event from e-buses
		• Simulations carried under the "uncoordinated scenario"
		  • "Depot charging scenario," where e-buses charging among the 20-charging depot available in Jaworzno. In this scenario 4 profiles are considered, which corresponds to the utilization of 5, 10, 15 or 20 EV chargers.
		  • "OppCharge," where 12 fast charging pantographs are deployed to support the bus fleet.
			• The study analyzed the e-buses impact on the grid based on voltage variation during charging events.
			• Under "uncoordinated charging," the voltage records a steep drop before gradually coming back to its normal value as the vehicles complete their charging. Under the "Oppcharge Scenario," similar results are observed.
			• Under the "coordinated charging," however, voltage remains more even throughout the charging events

Elaadnl (2022)	Netherlands	• Fleet: Electric passenger cars, vans, and trucks • Charging strategy: Mostly through overnight depot charging (85% of the fleet demand) but also including public charging (15% of the fleet demand) • Grid impacts are analyzed at the national and local level based on modeling. For the local level studies, additional inputs were received from local companies and network operators.	The report presents a national and local level analysis where electric vehicles impact on the grid were analyzed. For the national level analysis, the study found that an additional 16.7 TWh of electricity will be needed to accommodate the electric van and truck fleets by 2050 (15% of the current national consumption). This raise concerns in more than 500 industrial sites (15% of the total) that are already experiencing congestions or have given advance notices. The analysis also show that smart charging could reduce trucks overnight peak load demand by up to 50% on an average day. For the local level analysis, the study focuses on Lage Weide (Utrecht), De Dubbelen (Meierijstad), and Centerpoort (Zwolle). The study found that as the fleet of electric vehicle increases over the 2025–2035 timeframe, the three locations are impacted differently. • At the Centerport location, the substation experiences congestion in 2025. A new substation is planned to be installed in 2027. Additional medium voltage grid upgrades are currently under construction and expected to be ready at the end of 2024. No additional grid updates are expected until 2035 • In De Dubbelen, the transmission network will need to be expanded, to cope with the combined demand from EVs and other activities. This is expected to be completed by 2025. No additional upgrades are expected until 2035 • In Lage Weide, upgrades are needed between 2025 and 2030 to address insufficient capacity at a substation and cable overloading. With planned investments, substations are expected to present sufficient capacity, however cable overloading concerns may persist. A new transformer station will be ready in 2032.

Across the literature, three main trends can be identified regarding the impact of battery-electric trucks, or electric vehicles in general, on the electricity grid. First is that as more battery-electric trucks are being introduced on the roads, the more likely that they will have an impact on the grid. Second, necessary grid upgrades to address the impacts of battery-electric trucks occur at the distribution level, which encompasses the installation of new equipment such as substations, transformers, or feeders. It is also worth noting that distribution level upgrades typically cost less than generation or transmission level upgrades. In the case of the Netherlands, however, an increasing number of regions, mostly industrial sites, are in locations where the grid is already congested , and lengthy permitting processes are typically expected before the upgrades take place (Elaadnl, 2022). Third, the impact on the grid can be reduced through mitigation strategies to reduce peak load events. Most of those mitigation strategies fall under smart charging and pricing schemes that encourage off-peak charging.

Based on discussions with regulators and public electric utilities, utilities should also consider redefining their business models to take into account novel demand from electric vehicles. Under the traditional electric utility regulatory model, utilities are given incentives to keep the costs low for all customers and to deliver electricity to buildings, which is less suited for proactively addressing the charging requirements of electric vehicles. Because utilities operate under a “first come first served” principle for grid connection and upgrade requests, significant waiting times and delays can occur. New electric utility models are needed to manage electric vehicle-related load and provide grid connections in advance of demand. More information is provided on this topic in the last section of this paper summarizing lessons learned and remaining barriers.

POLICIES AND PROGRAMS TO SUPPORT CHARGING SOLUTIONS FOR BATTERY-ELECTRIC TRUCKS

Governments have many opportunities to accelerate the rollout of charging infrastructure and reduce costs to ensure that targets can be met. These include pilot programs and public-private partnerships to build economies of scale and generate best practices, financial incentives for early movers or priority applications, and regulations to set the pace of rollout and clarify roles and responsibilities of different actors. This section provides examples of leading policies within each of these categories from the major markets of China, Europe, and North America.

NORTH AMERICA

Pilot programs

The deployment of zero-emission trucks and the associated infrastructure in North America is concentrated along the Pacific coast, particularly in areas which have seen high sales of light-duty ZEVs and have strong commitments to fully transition to ZEVs. Examples of pilot programs in this region are presented in Table 8.

Table 8. Examples of charging infrastructure deployment programs for battery-electric trucks in North America

Stakeholders	Type	Program	Source
California, Oregon, Washington	Corridor initiative	The West Coast Clean Transit Corridor Initiative: Sixteen electric utilities in California, Oregon, and Washington are partnering to build a corridor of high-power charging stations along the Interstate 5 and connecting highways from San Diego to British Columbia. This initiative set an initial target of 27 charging sites to be installed by 2025, with a plan to expand 14 of them in 2030 when an estimated 8% of trucks on California roads will be electric.	West Cost Clean Transit Corridor Initiative (2020)
CARB, Volvo Trucks, the South Coast Air Quality Management District, and 12 other organizations	Funding initiative (2019–2022)	Volvo LIGHTS (Low Impact Green Heavy Transport Solutions) initiative**:** The three-year program, funded by a $48.8 million investment by CARB, brings together multiple stakeholders to conduct pilot projects to demonstrate how, through innovative solutions, charging logistics can be optimized for battery-electric trucks. For example, a project in Chino, CA, involves on-site smart charging enabled through cloud software to help mitigate grid impacts and reduce charging costs.	Volvo Lights (2021b)
California	Funding initiative	Funding of up to $2 million per applicant aims to support projects that develop innovative charging solution technologies and business models to support the deployment of light medium and heavy-duty vehicles. For medium and heavy-duty vehicles, the program focuses in two areas: 1) minimizing operating, purchase and/or installation costs 2) advance customer charging interface to make charging events user-friendly.	California Energy Commission (2022)
Damier Trucks North America and Portland General Electric (PGE)	Research and development	Electric Island**:** A large site that contains eight medium- and heavy-duty charging stations. It will serve as a pilot project to study energy management, charger use, and medium and heavy-duty vehicle performance. The site is intended to support continuous charging technology advancement and will therefore integrate upcoming megawatt chargers once they become available.	Daimler Truck (2021)
British Columbia	Funding initiative	CleanBC Go Electric Commercial Vehicle Pilots (CVP) Program**:** The $19 million program provides funding (up to a third of total costs) and support for vehicle purchases and infrastructure installation in exchange for data on performance to inform wider deployment. Businesses, non-profits, local governments, and Indigenous communities are eligible to apply for the program.	CleanBC (2020)
Volvo Truck North America, Volvo Financial Services, Volvo Technology of America, Shell Recharge Solutions TEC Equipment, Affinity Truck Center, and Western Truck Center	Corridor initiative	The Electrified Charging Corridor Project**:** Funded through a $2 million award program from the California Energy Commission, the project aims to construct high-powered, publicly accessible charging stations for long range medium and heavy-duty vehicles across Central and Northern California. It aims to accommodate different user profiles, including the smaller business fleets that would rather avoid investing in large scale charging infrastructure, fleet owners looking into piloting electric vehicles, or fleets that rely on publicly available chargers when on the roads.	WorkTruck (2022)

Funding initiatives for charging infrastructure

Several jurisdictions across North America have implemented incentive programs to facilitate the acquisition of battery-electric truck chargers. Some of these programs are listed in Table 9.

Table 9. Examples of funding available for battery-electric truck chargers in North America

Jurisdiction	Amount	Description	Source
Québec	50% (or up to $60,000) of the cost of a DC fast charger	The Transportez Vert program is intended to promote the electrification of vehicle fleets by providing financial assistance for the purchase and installation of fast-charging stations	Government of Québec (2022)
California	Funding initiative awarding up to $2 million per applicant	The funding supports projects that develop innovative charging solution technologies and business models to support the deployment of light medium and heavy-duty vehicles. For medium and heavy-duty vehicles, the program focuses on minimizing operating, purchase and/or installation costs, and improving the customer charging interface to make charging events more user-friendly.	California Energy Commission (2022a)
	Up to $500,000 for electric charging infrastructure and 2 million for hydrogen stations, plus an additional $750,000 for electric charging and $3 million for hydrogen station when equity criteria are met	Announced in 2021, the Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE Commercial Vehicles) initiative aims to support the deployment of electric and hydrogen charging stations for trucks.	California Energy Commission (2022b)
	A total of about $23 million is available for phases 1 and 2 of the grant	Released in 2020, the funding aims to support applied research and development, technology demonstration and deployment, and to the deployment of high-power corridor charging solutions for trucks.	California Energy Commission (2022c)
	$44.1 million funding initiative	The grant program aims to support the large-scale deployment of zero-emissions class 8 drayage and regional haul trucks, along with the charging infrastructure needed for their operation.	California Energy Commission (2022d)
New York state	As of 2020, 85% of the utility-side costs, with incentives capped at $1.2 million per participant	Con Edison's charging infrastructure program objective is to lower diesel emissions by supporting the transition towards electric medium-and heavy-duty fleets. It this effect, the program provides incentives that reduce utility-side costs when installing DC fast chargers.	ConEdison (2022)
	$700 million	The goal of the EV Make Ready initiative is to deploy more than 500,000 charging stations by 2025 across light, medium, and heavy-duty fleets.	NYSERDA (2020)
	$206 million	Targeted to Environmental Justice communities, this fund was created to make sure the EV Make Ready initiative is equitable.	

Regulations and government programs

Early adopters of electric trucks cite several challenges when trying to reduce the charging infrastructure implementation timeline, particularly with finding and acquiring the land, and upgrading the grid (ICCT, 2022). Other significant challenges include lengthy permitting processes, delays in electric utility connection, environmental compliance, inspection schedules, uncertainty around standardization, and the lack of personnel capacity in local governments.

California is undertaking several measures to overcome these challenges. A successful rollout of electric trucks will require a holistic approach to transportation planning. With this in mind, the California Energy Commission (CEC) is conducting an $8 million grant solicitation to identify the actions and milestones needed for electric truck charging infrastructure deployment. These projects should be completed by 2024. In addition, the CEC is examining grid impact with two different tools. The HEVI-LOAD model analyzes truck travel patterns, load curve scenarios, and charging demand to inform where loads could exist and behave through time (Wang et al. 2021). The EVSE Deployment and Grid Evaluation (EDGE) tool seeks to integrate the HEVI-LOAD modeling results with utility grid capacity data to inform users about how those loads could impact certain regions.

Another key action undertaken by California is engagement with stakeholders through the California Zero-Emission Vehicle Market Development Strategy, implemented by the California Governor's Office of Business and Economic Development (GO-Biz), which includes Agency ZEV Action Plans that identify infrastructure as a key pillar of action. The CEC communicates with electricity providers, works with GO-Biz to streamline permitting process, and monitors and participates in activities organized by industry groups such as CharIn who is working on industry standardization (Go-Biz, 2021)

In 2021, the California Public Utilities Commission approved a new tariff bill (Rule 29) that makes investor-owned electric utilities responsible for their associated make-ready infrastructure, including distribution lines, transformers, trenching, and construction, among other elements. Consumers with electric vehicles are responsible for the charging equipment cost, including those related to planning, design, or installation. It is estimated that Rule 29 could reduce charging infrastructure installation costs by about 25% (Muller and Baumhefner, 2021). Charging operators involved in Rule 29 must commit to a 5-year contract, consistent with the need to supply durable charging solutions to sustain the ZEV transition (Muller and Baumhefner, 2021; California Public Utilities Commission, 2021).

CHINA

China's electric vehicle charging infrastructure policies usually cover all types of electric vehicles and are rarely tailored specifically to electric trucks. These include pilot programs, funding programs, and rate design programs.

Pilot programs

In October 2021, China launched a two-year pilot program to promote the application of battery swapping technology. A total of 11 cities were selected as the first batch of pilot cities: Beijing, Nanjing, Wuhan, Sanya, Chongqing, Changchun, Hefei, Jinan, Yibin, Tangshan, and Baotou. The last three cities are expected to fully focus on heavy-duty truck applications, while the previous eight cities will demonstrate battery swapping on both electric cars and heavy-duty trucks. The Chinese central government aims to put at least 100,000 battery swapping-enabled electric vehicles on the road and build at least 1,000 battery swapping stations through this pilot program (MIIT, 2021).

Each city involved in the pilot program will develop a local implementation plan and propose their own targets for battery swapping applications. All three pilot cities focusing on heavy-duty truck applications have proposed ambitious targets on battery swapping station construction and battery swapping-enabled heavy-duty truck deployment, as is shown in Table 10. The other eight pilot cities also include heavy-duty truck application in their implementation plans, although battery swapping application on taxis, ride-hauling vehicles, and private cars are emphasized.

Table 10. Battery swapping activity targets proposed by three pilot cities focusing on heavy-duty truck applications

Pilot city	Targets for battery swapping station construction	Targets for battery swapping-enabled heavy-duty truck deployment	Source
Yibin	20 by 2023 60 by 2025	1,000 by 2023 3,000 by 2025	Sichuan Daily (2021)
Tangshan	60 by 2023	2,600 by 2023	Tangshan Municipal Commission of Economy and Information Technology (2021)
Baotou	60 by 2024	3,000 by 2024	Baotou Daily (2021)

Funding programs

China initiated its electric vehicle charging infrastructure funding program in 2014, through which the Chinese central government provided funding to provincial-level governments to support local electric vehicle charging infrastructure development (MOF, 2014). To qualify for the funding, a province must meet specific electric vehicle sales criteria set by the Chinese central government, which vary by province and tigthen year by year. For example, Hainan province must hit annual electric vehicle sales of at least 70,000 and an electric vehicle sales share of at least 6% to qualify for the 2020 funding. The exact funding each province could receive increases with its annual electric vehicle sales and was capped at ¥200 million (~ US$31 million) per province in 2020 (MOF, 2016). Through November 2020, the Chinese central government invested ¥ 4.5 billion (~ US$0.7 billion) into electric vehicle charging infrastructure through this program (Chinese Central Government, 2020).

Taking advantage of the funding from the Chinese central government, each province develops its own local subsidy programs to support the construction and operation of electric vehicle charging infrastructure, including charging infrastructure that fits the needs of electric heavy-duty trucks. For example, in Hainan province public chargers could receive a one-time construction subsidy of ¥100 (~ US$16) per kilowatt of rated power to public chargers, up to 10% of the equipment cost, and an annual operation subsidy of ¥0.1 (~ US$0.016) per kilowatt hour of electricity charged, up to ¥200 (~ US$31) per kilowatt of rated power per year during 2021–2025. Hainan province also provides a one-time subsidy equal to 10% of the equipment cost to battery swapping stations during the same time period (Hainan Provincial Development and Reform Commission, 2019). Similar electric vehicle charging infrastructure subsidy programs exist in almost all provinces of China, although the exact subsidy levels vary.

Starting in 2021, the Chinese central government no longer provides funding to provincial-level governments. However, many provincial and municipal-level governments continue to provide subsidies to support local charging infrastructure construction and operation using their own funds.

Rate design programs

China initiated its electric vehicle charging rate design program in 2014, which proposed four major principles to reduce the fuel costs of electric vehicles (NDRC, 2014). Provinces and cities should follow these principles when they develop their local policies on electric vehicle charging rates, with exact policies varying by region.

First, public charging stations and battery swapping stations were exempt from the demand charge of the large industrial customer rate until the end of 2020. For example, public charging stations and battery swapping stations in Fujian province only needed to pay half of the large industrial customer rate through 2020 (Fujian Development and Reform Commission, 2019). Starting from 2021, this incentive is no longer offered in Fujian; however, some other jurisdictions, such as Shandong province, are still offering such an exemption as a way to accelerate vehicle electrification.

Second, electric vehicle charging and battery swapping stations receive time-of-use electricity rates. Electric vehicles are encouraged to charge at periods of low system-wide power demand to reduce fuel cost and, at the same time, increase grid utilization efficiency. The exact policy design of time-of-use rates vary by province. For example, in Guangdong province, electric vehicle charging rates at peak (10 a.m.–12 p.m. and 2 p.m.–9 p.m.) and valley (12 a.m.–8 a.m.) periods in 2022 are 1.7 and 0.38 times the rates at flat periods, respectively (Guangdong Development and Reform Commission, 2021).

Third, electric vehicle charging service fees, which are charged together with electricity rate at public stations, were capped at a certain level until end of 2020. The exact upper limits are determined by local governments, usually ranging from ¥0.5 (~US$0.08) to ¥1.6 (~US$0.25) per kilowatt hour (EVPartner, 2016). Starting from January 1, 2021, some jurisdictions continue to set upper limits on electric vehicle charging service fees, while the others have transitioned to fully rely on market mechanisms to determine local electric vehicle charging service fees.

Fourth, electric vehicle charging stations and battery swapping stations do not need to pay the cost of necessary construction or upgrades of the power grid to enable their smooth operation. Instead, China's two state-owned grid companies, State Grid and China Southern Grid, are responsible for helping these stations to access the grid and the relevant transmission and distribution costs are borne by the grid companies.

EUROPE

Pilot projects and industry programs

Multiple pilot projects commissioned by governments and industry-led programs are occurring in Europe and are described in Tables 11 and 12.

Table 11. Select examples of pilot projects and industry programs in Europe

Stakeholders	Type	Description	Source
Siemens Mobility, Sweden and Germany	Overhead catenary pilot	Test in Sweden in 2016 in a 2km section on the E16. Test in Germany in 2018, 10km in the state of Hessen.	Siemens (2017)
UK Department for Transportation	Funding to develop innovative solutions for the uptake of zero emission trucks	£20m in 2021–2022 to support industry to conduct feasibility studies on developing cost-effective, zero-emission heavy goods vehicles and their associated infrastructure in the UK. A further £200m has been announced to undertake real-world at-scale demonstrations of three zero emission HGV technologies	UK Government (2021)
German government and 20 partners, including truck manufacturers and charging infrastructure providers	HoLa megawatt charging project	Funded by the German government. Four locations along the A2 federal highway were selected for the deployment of two megawatt charging systems each.	Langendorf (2022)
Netherlands government, entrepreneurs, knowledge institutions, and NGOs	Innovation projects for sustainable transport.	A subsidy for the demonstration of climate technologies and innovations in transport (DKTI-Transport) has been created to help the Netherlands achieve its Climate goals. One project is focused on the development of a roadmap for electrification of the waste collection truck fleet.	Rijksdienst voor Ondernemend Nederland (n.d.)

Table 12. Select examples of industry programs in Europe

Stakeholders	Type	Description	Source
Volvo Group, Daimler Truck and Volkswagen Group's Traton Group	Binding agreement signed in 2022, including funding	The Commercial Vehicle Charging Europe is a joint venture for a heavy-duty charging network in Europe, based in Amsterdam. The parties committed to investing €500 million, €167 million each. By the end of 2026, the network is expected to reach 1,700 charging points along highways, at logistics facilities, and at destination locations.	Commercial Vehicle Charging Europe (2022)
CharIn	Charger construction guide	The guide includes requirements on space to be made available between each station to ensure accessibility for large trucks, and the recommended location of the transformer, the switch board, and the equipment storage unit.	Black & Veatch (2021)
Netze BW Division Service and Daimler Truck	Charging concept trials to meet operational needs	Netze BW Division Services and Daimler Trucks is building a demonstration charging park for e-trucks at Mercedes-Benz production site in Wörth, Germany to allow commercial vehicle customers to try various charging concepts to determine which of them best meets their operation needs.	Netze BW (2022)

Funding programs

Similar to the United Kingdom's funding program mentioned above, several European countries are providing funding for truck charging infrastructure solutions. These fundings can be classified in three categories: innovative solutions, charging infrastructure purchase and installation, and connection to the grid, and are presented in Table 13.

Table 13. Selection of European heavy-duty vehicle charging infrastructure funding programs

Country	Amount	Description	Source
France	60% of the cost of a truck charger on private parking	Grant available for the first 1,000 charging points applications	ADVENIR (2021)
	€960,000 for grid connections above 8 MW	Grant is applicable for chargers with a power output above 500 kW	
Germany	€1.6 billion by 2024 for truck electrification	This fund will be allocated through four calls to projects per year and cover the cost of feasibility studies, new electric truck purchases, and charging infrastructure. A single company will be able to receive a maximum of €15 million per year	Bundesamt für Güterverkehr (2021)
The Netherlands	Tax deduction with a budget of €169 million for 2022	45% deduction of environmentally friendly investments and 75% depreciation available for entrepreneurs.	Netherlands Enterprise Agency (2021)
European Union	€1.575 billion	The Connecting Europe Facility (CEF) includes a proposal under the Alternative Fuels Infrastructure Facility (AFIF) to support the deployment of alternative fuel supply infrastructure and contribute to the decarbonization of transport along the TEN-T network. The AFIF will fund action only in combination with financial support from financial institutions (such as the European Investment Bank) to achieve a higher impact and foster private sector involvement.	European Commission (2021)

Additional charging infrastructure incentives and programs can be found in a previous ICCT report (Xie & Rodríguez, 2021).

Regulations and government programs

In July 2021, the European Commission released a proposal for an alternative fuel infrastructure regulation (AFIR) as part of its "Fit for 55" package. The proposed regulation would set mandatory targets for the deployment of infrastructure for charging and hydrogen refueling for both light- and heavy-duty vehicles. Provisions set minimum requirements for the rollout of infrastructure serving zero-emission HDVs across the Trans-European Network for Transport (TEN-T) and related urban nodes, and at overnight truck parking areas. The key elements of the Commission's proposal are summarized in Table 14 (Ragon et al., 2022).

Table 14. Key elements of the European Commission's proposal on the Alternative Fuel Infrastructure Regulation (AFIR)

Scope	Metric	Commission's proposal
TEN-T core network	Power of recharging pool every 60 km per direction	1,400 kW by 2025 3,500 kW by 2030
	Minimum charging speed of highest-power charging station per pool	350 kW
TEN-T comprehensive network	Power of recharging pool every 100 km per direction	1,400 kW by 2030 3,500 kW by 2035
	Minimum charging speed of highest-power charging station per pool	350 kW
Urban nodes	Aggregated power output at each urban node	600 kW by 2025 1,200 kW by 2030
	Minimum charging speed of highest-power charging station per pool	150 kW
Safe and secure parking areas	Minimum number of charging stations with at least 100 kW	1 station by 2030
Hydrogen refueling stations (HRS)	Distance between HRS (> 2 t/day) on TEN-T network	150 km by 2030, 700 bar 450 km by 2030, liquid
	Urban nodes	At least 1 HRS by 2030

As of the end of 2022, this regulation is at the trialogue stage with negotiations between the three EU regulating authorities (Commission, Parliament, and Council). Once the three parties reach a compromise, this regulation will become law. This will most likely happen in 2023.

The Council of the European Union published its agreement in June 2022 (Council of the European Union, 2022). The agreement removed the 2025 targets for the core and comprehensive network and replaced them with a requirement of 15% of the length of the network to be served by charging pools with at least 1,400 kW in 2025 and 40% in 2030, with a minimum power output of 2,800 kW for the core network and 1,400 for the comprehensive network. Additionally, the agreement introduced derogations for portions of the TEN-T network with low traffic. Portions with fewer than 2,000 HDVs per day may have only one charging pool for both direction and Member States may comply with 50% of the power output requirements. Portions with less than 800 HDVs per day may increase the minimum distance between charging pools from 60 km to 100km. These derogations would be reviewed every 2 years.

The European Parliament published its agreement in October 2022 (European Parliament, 2022). The agreement increases the power output requirements for 2025, 2030, and 2035 at both the pool and the station level while allowing for lower power outputs in low-traffic corridors. The EU Parliament also amended the proposal on hydrogen stations, pushing for more stations and faster deployment. Additionally, Members of Parliament suggested the addition of provisions for smart and bi-directional charging, charger maintenance, ensuring sufficient grid capacity, and user-friendliness in terms of providing information on availability and pricing at stations across Europe. Members also emphasized the importance of preventing monopolies and fostering competition between charge point operators.

In addition to charger and power requirements, the AFIR proposal outlines requirements for a user-friendly charging infrastructure. This includes provisions on accessibility, payment options, price transparency, consumer information, smart charging, and signposting rules for electricity supply. In addition, the proposal provides technical specifications, including requirements for the full technical interoperability of the recharging and refueling infrastructure in terms of physical connections and communication exchange.

As previously mentioned, early electric truck adopters face challenges concerning charger accessibility due to the length of time required to find the land, a lengthy permitting process, the time required to upgrade the grid, and knowledge gaps between the different stakeholders. To overcome these challenges, the Netherlands included a national charging infrastructure agenda as part of their Climate Agreement (Nationale Agenda Laadinfrastructuur, 2020). The multi-year policy agenda consists of a set of agreements between various public and private stakeholders to meet charging needs based on the government's electrification goals. This agenda highlights key actionable items for all stakeholders in five categories: 1) Charging infrastructure deployment scale and location, 2) Price transparency, open protocols, and open markets, 3) Smart charging, 4) Innovation, and 5) Logistics. The logistics action items are further split into various task forces assigned with addressing barriers and opportunities around data, private charging, public charging, and charging infrastructure for construction vehicles (NAL, n.d.).

LESSONS LEARNED FROM CHINA, EUROPE, AND NORTH AMERICA AND REMAINING CHALLENGES

As discussed in the previous section, governments have pulled many levers to leverage private capital, in concert with targeted public funds, to efficiently deploy, operate, and maintain charging infrastructure for battery-electric trucks. However, many challenges remain. This section summarizes lessons that can be learned and identifies the remaining barriers and policy gaps.

LESSONS LEARNED

The different actions undertaken by governments include pilot programs and public-private partnerships to build economies of scale and generate best practices, financial incentives, and regulations to set the pace of rollout and clarify the roles and responsibilities of different actors. The following lessons can be learned from the three regions analyzed:

Charging infrastructure roadmaps, followed by pilot programs and public-private partnerships, are key to generating best practices and building economies of scale. The battery-electric truck market is still at an early stage. Pilot projects such as the Electric Island in Portland can help to understand energy management strategies and charger utilization. Additionally, testing novel technologies, such as battery swapping in Yibin, Tangshou and Baotou, China, wireless charging in Sweden, and overhead catenary charging in Germany, can help to evaluate each technology use case. Public-private partnerships, such as HoLa in Germany testing megawatt chargers and Volvo LIGHTS in California generating knowledge on the optimization of charging logistics, are crucial for generating best practices and bringing the private sector on board. However, it is important to note that while charging technology pilot projects are still relevant, grid-side investments do not require new technology or pilot projects and, given the long lead times required, should begin immediately.

Financial incentives targeting both charging infrastructure and the grid are key in the early market. In the early stages of electric vehicle adoption, a positive business case for charging infrastructure deployment is difficult due to potential low charging infrastructure utilization. However, public funding can initialize and accelerate infrastructure deployment. Funding provided by governments include capital for research and innovation, purchase and installation, and connection to the grid. For example, the UK Department for Transport's has established a £20 million fund for innovative solutions to decarbonize trucks. To assist with the purchase and installation, France covers 60% of charger costs of private parking. To facilitate connection to the grid, New York state covers 85% of the utility-side costs when installing chargers, with incentives capped at $1.2 million per participant. Finally, the European Union fosters private sector involvement through its blending mechanism, providing funding for charging infrastructure deployment only if financial institutions also contribute.

Regulations are needed to set the pace of deployment and clarify stakeholders' roles and responsibilities. Binding installation targets and regulations provide greater policy certainty for all stakeholders and encourage investments from the private sector. As an example, the European Commission proposed a regulation on heavy-duty truck charging infrastructure setting power-based and distance based-targets for charging hubs for different time horizons and traffic corridors. Besides roll-out targets, regulating the roles and responsibilities of stakeholders gives clarity to the market. California allowed electric utilities to rate-base their infrastructure costs for investor-owned companies since they are responsible for utility-side make-ready infrastructure, including distribution lines, transformers, trenching, and construction.

REMAINING BARRIERS

Even though governments are taking actions to enable the fast and efficient deployment of charging infrastructure for battery-electric trucks, several challenges remain to be addressed.

Upfront coordination between electricity utilities, commercial fleets, transport authorities, and energy commissions is critical. Electric vehicle charging infrastructure is a cross agency-topic; coordination and the efficient utilization of the already existing communication channels between relevant agencies and electricity utility regulators is key. Constant communication between designated persons in each agency working from a single common plan, consulting commercial fleets, and undertaking common actions is critical to address knowledge gaps between stakeholders, streamline policy implementation, and reduce charging deployment time and cost.

Understanding and reducing the major sources of delays is key. Charging deployment is composed of many steps, with some of them creating significant delays in the process. Major sources of actionable delays include permitting processes, environmental compliance, inspection schedules, and grid upgrades. All of these delays could be reduced through upfront coordination between agencies. For example, inspections could be streamlined through inspector education programs to avoid *ad hoc* interpretation of local electrical codes, and schedules could be set in advance and updated as needed based on project timelines. The attainment of multiple permits could be bundled under a single permitting process with upfront coordination between the different permitting authorities. For grid upgrades, upfront planning, understanding of the demand, and close coordination is critical. More consistency in the time it takes to perform each step would give confidence to fleets to make the transition to battery-electric technology.

International coordination on interoperability, software and hardware standardization, and charging user-friendliness would be beneficial to governments. Charge point design and technical specification regulations can ensure a well-functioning market that allows for an efficient transition to electric. Charge point design regulations include public charger accessibility, payment options, price transparency, consumer information, smart charging, and signposting. Technical specifications include interoperability requirements in terms of physical connections and communication exchange, and uptime requirements. The European Commission has proposed regulation in these areas, but further regulations and international discussions are critical. For example, the ZEV Alliance organized a fruitful deep-dive discussion on public charger reliability, including defining uptime requirements and other challenges, with stakeholders from many different jurisdictions (ICCT, June 2022). These international discussion and coordination are key to accelerating the deployment of charging infrastructure across regions.

The ZEV transition requires new skills across all stakeholders, and governments could identify and help build up the new skills required to successfully transition to electric trucks. Many countries are facing an EV skills gap, which shows a potential for job creation. There is a lack of qualified personnel in local and national governments, electricity utilities, and other stakeholders with the necessary skills to develop, produce, and maintain charging infrastructure. Governments should work together with the private industry to unlock new business opportunities and job creation through identification of these shortages and creation or facilitation of training programs.

Electricity utility business models and regulations could be modified to adopt to electric vehicles. For decades, electricity utilities have delivered electricity to buildings, the requirements of which are significantly different than electric vehicles. Electricity utilities have been incentivized to keep costs low for all customers, which discourages upgrades to the grid which would address future demand. Governments would benefit from rethinking the way they regulate electricity utilities. Electricity utilities could modify their business models and, for example, distribute grid upgrade costs over long periods of time and include them as surcharges in the contracted rate design.

CONCLUSIONS

The battery-electric truck market is still in its early stages, with approximately 20,000 units sold in 2021, with most of these units being medium- rather than heavy-duty. However, significant growth is expected in the coming years as more governments and truck manufacturers are setting targets to phase-out of combustion engine truck sales. This growth in electric trucks on the road needs to be supported by a significant deployment of charging infrastructure. This paper analyzed the charging solutions for battery-electric trucks, the grid impact of these vehicles, and highlighted key policies and programs in different regions of the world to facilitate the buildout of charging infrastructure. As result, we draw the following conclusions:

Early electric trucks have relied on light-duty infrastructure, but more powerful standards are ready for commercialization. Wired stationary charging options range from AC slow with power below 43 kW, to DC fast charging with power up to 350 kW. However, higher power standards are under development. ChaoJi in China will be able to deliver up to 900 kW and the MegaWatt Charging System in Europe and North America could deliver up to 3.75 MW. Different charging speeds can serve different use cases for electric truck fleets: overnight at depot private or public in rest areas along highways (100kW), public opportunity fast charging during rest or loading and unloading (up to 350 kW), and public opportunity ultra-fast charging (above 1MW). Standardization of chargers is key to reducing development costs for both truck and charger manufacturers, ensuring interoperability, and ensuring that an international used ZEV market can flourish.

Novel alternatives to wired stationary charging are being tested to increase flexibility. Battery swapping, wireless charging, and overhead catenary charging are three emerging alternative charging solutions. These technologies could reduce charging downtime and reduce the upfront costs of battery-electric trucks due to reduced battery size. However, deployment of these technologies face political and business challenges. Battery swapping for HDVs has mostly been promoted in China, and its future largely depends on economies of scale and if battery design and placement in the truck could be standardized. Wireless in-road charging is still at the demonstration stage and is associated with high upfront infrastructure costs and the additional cost of equipping trucks with receiver pads. Several overhead catenary pilot projects are underway in Europe. Both wireless and overhead catenary charging shift some of the costs away from the vehicle to public charging infrastructure. Indeed, with these technologies, there is a compromise to find between the length and location of electrified road and the truck's battery size. For these technologies to function, standardization between countries is required to allow for cross-country travel.

Advanced planning and smart charging are key to managing electricity demand in a time- and cost-efficient way. Grid upgrades significantly add cost and time constraints to the uptake of battery-electric trucks, making advanced planning and grid management strategies key. Two case studies on Germany and the United States were conducted to assess energy, charging infrastructure, and power output needed up to 2040. Results show that in 2040, battery-electric truck energy needs will represent 6% of Germany's electricity production and 3% of United States'. This does not imply that a 6% and 3% increase in grid capacity will be needed, since the existing infrastructure can be leveraged through demand management. Electric trucks will require 715,000 chargers in Germany and 2.3 million chargers in the U.S. in 2040. The grid impacts of electric trucks can be managed through a revision of public electric utility business models; upfront coordinated planning between electric utilities, transport authorities, energy commissions, and all the other relevant stakeholders; and through the implementation of smart charging solutions.

Regulating charging density based on traffic volumes and updating public electric utility business models can ensure that charging infrastructure is built alongside truck deployment at a reasonable cost. The European Union was the first jurisdiction to propose a regulation for charging infrastructure for heavy-duty vehicles. This regulation sets traffic-based targets on the power output of charging hubs and the distance between them. On the grid side, in 2021, the California Public Utilities Commission approved a new tariff bill that allows electric utilities to modify ratepayer tariffs in order to cover utility-side make-ready infrastructure costs. It is estimated that this bill could reduce charging infrastructure installation costs by 25% but would increase ratepayers' costs over time. A similar regulation in place in China requires the two state-owned grid companies to help station operators access the grid and bear the relevant cost. Coordination between multiple government agencies, electricity utilities, and commercial fleets is key to the successful planning and installation of charging infrastructure to support electric trucks.

In the early market, support through pilot projects and financial incentives can build confidence and scale. Most jurisdictions offer funding for battery-electric truck charging infrastructure, which can be classified into three categories: research and innovation, purchase and installation, and connection to the grid. Some financial incentives, such as the EU blending mechanism, also foster private investment through cost-sharing requirements. In addition to financial incentives, several pilot projects are also underway to test emerging technologies such as megawatt charging systems, catenary charging, battery swapping for trucks, and smart charging for battery-electric truck fleets.

Several challenges regarding battery-electric truck charging infrastructure deployment still need to be addressed. Although governments are taking actions to enable the fast and efficient deployment of charging infrastructure for battery-electric trucks, there is still room for improvement. Extensive upfront coordination between electricity utilities, commercial fleets, transport authorities, and energy is critical. Governments could specifically work with electric utilities on new business models to adapt to EV needs, and with all stakeholders to understand charging deployment delays and mitigate them. Finally, the ZEV transition is demanding new types of skills, and governments could identify these skills and work to overcome personnel shortages and leverage these new skills to create jobs.

This analysis points to several other areas for future research. An important next step would be to estimate the ideal mix of wired stationary charging types and emerging solutions based on fleet requirements and national policy strategies. Future work could also investigate the impacts on the electric grid and required upgrade costs at the local level. Detailed strategies and policy guidance would ensure that the pace of charging infrastructure deployment does not slow the uptake of battery-electric trucks and would promote private sector investment.

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