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ZEV TRANSITION COUNCIL

Deploying charging infrastructure to support an accelerated transition to zero-emission vehicles

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The Zero Emission Vehicles Transition Council is an international forum focused on enhancing political cooperation on the transition to zero emission vehicles (ZEVs).

It brings together Ministers that represent over 50% of the global car market. Council members have agreed to collectively address some of the key challenges in the transition to ZEVs, enabling the transition to be faster, cheaper, and easier for all.

The Council will convene on a regular basis to discuss how to accelerate the pace of the global transition to ZEVs, to reduce emissions and help the global economy meet our goals under the Paris Agreement.

Acknowledgments

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Executive Summary

Vehicles and fuels are a system. Achieving the widespread adoption of light and heavy zero-emission vehicles (ZEVs) envisioned by many at COP26, including as described in the ZEV Declaration and the Global Memorandum of Understanding (MOU) for Zero-Emission Medium- and Heavy-Duty Vehicles, is contingent upon deploying charging infrastructure at a scale and pace that can meet these goals. This briefing uses modeling to assess how much charging infrastructure will be needed in Zero Emission Vehicles Transition Council (ZEVTC) member jurisdictions through 2030 to match an accelerated transition to ZEVs. It also provides details of policy approaches to accelerate deployment of this infrastructure.

Infrastructure deployment needs to ramp up considerably to align with ZEV ambition. Previous work for the ZEVTC showed that for the emissions from road transport to align with Paris Agreement goals, approximately 80% of new light-duty vehicle (LDV) sales and 45% of heavy-duty vehicle (HDV) sales need to be zero-emission by 2030.[1] Both segments need to reach 100% of new sales no later than 2040. Under the Paris-aligned scenario, we estimate here that ZEVTC members will need 6 million public charge points for LDVs and 200,000 public charge points for HDVs by 2030. This would require 240 GW of installed power output. As of mid-2022, just 13% of the public chargers and 10% of the installed power output needed in 2030 were already in place. Beyond public charging, ZEVTC jurisdictions are estimated to need approximately 95 million private chargers by 2030.

Deployment cannot be delayed further or postponed. To keep pace with rapidly growing ZEV demand, robust public charging networks need to be built before 2030. As infrastructure requires careful planning and takes time to be installed, governments should act now to ensure infrastructure build-out is not a barrier to rapid ZEV transitions. This means sustained growth in public chargers with adequate power output. For LDVs, the yearly growth rate of installed public charging power output needed between mid-2022 and 2030 is estimated to range from 7%–8% in the Netherlands and Norway to over 50% in India and Mexico. For HDVs, the same countries are at both ends of the spectrum, with a 26% yearly growth for Norway and up to 59% for India. For LDVs, Norway and the Netherlands are on track and are even exceeding the required growth levels; markets further behind will need to speed up. For HDVs, almost no public charging has been deployed so far.

The costs of infrastructure build-out can be shared with the private sector. The cost of hardware, installation, and planning for required public and private charging infrastructure in all ZEVTC jurisdictions would be approximately €336 billion over the period to 2030. Note that this is equivalent to 0.6% of the total gross domestic product (GDP) of ZEVTC members in 2021. Although the near-term costs are substantial, the societal benefits from a ZEV transition are larger. Additionally, a positive business case for building charging infrastructure has emerged in leading markets, including Norway and the Netherlands, where it is funded through public-private partnerships and utility ratepayers. As outlined below, collaboration between governments, car and truck manufacturers, energy companies, and infrastructure providers is crucial for filling the gaps in charging infrastructure deployment.

1 Josh Miller et al., "Decarbonizing Road Transport by 2050: Accelerating the Global Transition to Zero-Emission Vehicles," (ICCT: Washington, D.C., 2021), https://theicct.org/wp-content/uploads/2021/12/ZEVTC_Accelerating-transition_dec2021-2.pdf.

Governments are developing supportive policies to enable faster infrastructure rollout. Emerging government programs showcase that infrastructure policies need to include planning and coordination among stakeholders while limiting the use of public funds to things like closing gaps in the charging network and ensuring equitable access. Based on our review of policy approaches that support infrastructure, the following are priority areas for government focus:

- **Set binding installation targets for charging infrastructure to align with expected ZEV growth.** Designing infrastructure targets that align with the pace of ZEV growth would help ensure broader geographical coverage of chargers and that there is sufficient power output available ahead of demand. These targets are most effective in promoting ZEV transition when they carry binding obligations for public and private stakeholders to ensure that infrastructure deployment matches the needs of different vehicle types and travel patterns. Coordination between energy, transportation, and environment agencies and electricity utility regulators will streamline policy implementation and ensure smooth charging infrastructure rollout.

- **Use regulatory tools and incentives to address charging gaps and improve the business case for private investment.** Governments that seek to limit the role of public funding in the long-term need policy mechanisms that encourage efficient and faster deployment of private capital. Targeted regulations and allocation of public grants to the most challenging applications will improve the business case and promote equitable access. This will ultimately achieve scale more quickly and help ensure that more of the cost of infrastructure is shifted to the private sector over time.

- **Empower utilities to support ZEVs by designing electric vehicle-friendly rate structures and encouraging smart charging.** When utilities have a long-term view of grid requirements for the future vehicle fleet, they can plan for and invest in upgrading the grid effectively, if proper regulations are in place. Regulators can enable public and investor-owned utilities to pay for grid upgrades through phased introduction of new rate structures for electric vehicle charging. This can support new utility business models while limiting the impact on low-income electricity consumers. Promoting smart charging capability increases the utilization of existing capacity and can potentially defer unnecessary grid upgrades.

Introduction

ICCT has shown that an accelerated global transition to zero-emission vehicles (ZEVs) could reduce CO_2 emissions from on-road vehicles by 73% by 2050 compared with 2020 levels and align the road transport sector with an emissions trajectory that is consistent with Paris Agreement goals. To achieve this, the ZEV share of new vehicle sales in Zero Emission Vehicles Transition Council (ZEVTC) markets in 2030 would need to reach close to 80% for LDVs and 45% for HDVs and would need to grow to 100% for both vehicle groups no later than 2040.[2]

But vehicle sales are only part of the story, as these vehicles will need to be fueled throughout their lifetimes. Indeed, even in cases where consumer appetite for ZEVs

2 Arijit Sen and Josh Miller, "Emissions Reduction Benefits of a Faster, Global Transition to Zero-Emission Vehicles," (ICCT: Washington, D.C., 2022) https://theicct.org/publication/zevs-global-transition-benefits-mar22/.

is high, a lack of adequate charging infrastructure could hold the market back and potentially stall progress.[3]

Members of the ZEVTC are committed to collectively addressing key challenges in the transition to ZEVs and leading members have incentivized such infrastructure deployment in many financial and non-financial ways, notably through cost sharing with the private sector. This paper starts with a quantitative analysis of the amount and cost of charging infrastructure that we estimate will be needed across ZEVTC jurisdictions to match an accelerated ZEV transition that is aligned with the Paris Agreement.[4] It then summarizes effective policy approaches deployed by ZEVTC members to overcome common barriers.

Scale, pace, and cost of infrastructure deployment needed

ICCT carried out a modeling study to assess the infrastructure needs in ZEVTC member jurisdictions under an accelerated ZEV transition. In this section, we present the scale of infrastructure needs through 2030 for light and heavy vehicles, the pace at which this infrastructure would need to be deployed, and the cost of this infrastructure. Our approach follows the methods used in previous analysis and we consider how much vehicles are typically driven in each jurisdiction, vehicle efficiency, and access to home, workplace, and depot charging. Further details of the modeling are available in Appendix A.

We focus here on the two key metrics of infrastructure need, the *number of chargers* and *installed power output.*[5] A charger (or a charge point) is a device through which electricity is transferred from the grid to the electric vehicle. In the case of public chargers, these are categorized as either "normal" or "fast/ultra-fast."[6] Normal chargers deliver alternating current (AC) and can usually output a maximum of 22 kW. In comparison, fast and ultra-fast chargers deliver direct current (DC) and can usually output between 50 kW and 350 kW for fast chargers and up to 3.75 MW for ultra-fast chargers. Installed power output is the maximum power that a charger can deliver to an electric vehicle, usually expressed in kW. The higher the power output, the faster the vehicle is recharged. Installed power output is particularly relevant for governments' public charging planning because it gives more information on the number of electric vehicles that can be served on a given day. Conversely, for private charging, it is the number of chargers metric that matters a great deal. This is

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3 Peter Slowik et al., "Funding the Transition to All Zero-Emission Vehicles," (ICCT: Washington, D.C., 2019), https://theicct.org/wp-content/uploads/2021/06/Funding_transition_ZEV_20191014.pdf.

4 The focus of this paper is charging infrastructure deployment and we leave the assessment of hydrogen refueling infrastructure needs for future studies. Zero-emission technology choice depends on local vehicle types and travel patterns. Previous ICCT studies showed that fuel cell technology will be needed for some use cases in the heavy-duty segment, primarily for long-haul trucks that have heavy payloads and short overnight dwell times. Further note that, in this paper, the term "charging infrastructure" only pertains to wired charging. Other emerging charging solutions such as battery swapping and overhead catenary charging are not considered. Additionally, light-duty vehicles (LDVs) are passenger cars and light commercial vehicles, and heavy-duty vehicles (HDVs) encompass all buses and trucks above 3.5 tons. Two- and three-wheelers are not within the scope of this study. A glossary defining these and other relevant terms is in Appendix D.

5 Total installed power output is sometimes referred to as "total charging port capacity" in certain jurisdictions.

6 As the name suggests, fast chargers can serve a higher number of vehicles than normal chargers. To illustrate the difference between the two metrics, we can consider that a 50 kW charger counts as one charger and 50 kW of installed power output, and it can add up to 100 miles of range to an average battery electric car in 35 minutes. Meanwhile, an 11 kW charger also counts as one charger and 11 kW of installed power output, but it can only add up to 40 miles to an average battery electric car in 1 hour.

because private chargers are typically purchased by vehicle owners to serve one or a few vehicles. In this paper, private chargers include home chargers in apartments and houses, depot chargers (for vans, trucks, and buses), and workplace chargers. While workplace and depot chargers can sometimes be public or semi-public, they are all classified in the private category here.

Scale

Light-duty vehicles

Under an accelerated ZEV transition pathway, we estimate there will be nearly 153 million light-duty electric vehicles on the roads in ZEVTC jurisdictions in 2030. Most LDV charging happens at home and our modeling shows that powering this number of ZEVs will require about 93 million private charge points.

At the same time, public charging infrastructure for LDVs is important to spur user confidence, especially in the early stages of the transition, to allow for long journeys, and to provide charging for drivers who do not have home charging. Our modeling shows that powering the 153 million vehicles in 2030 will require 6 million public chargers. Figure 1 illustrates the number of public LDV chargers required in all ZEVTC jurisdictions in 2030. Note that, as of mid-2022, ZEVTC jurisdictions overall had only 13% of the public LDV charging points needed in 2030. Individual jurisdictions are at different stages in terms of public chargers and installed power output deployed as of mid-2022; this is shown in Figure 4 in the next section.

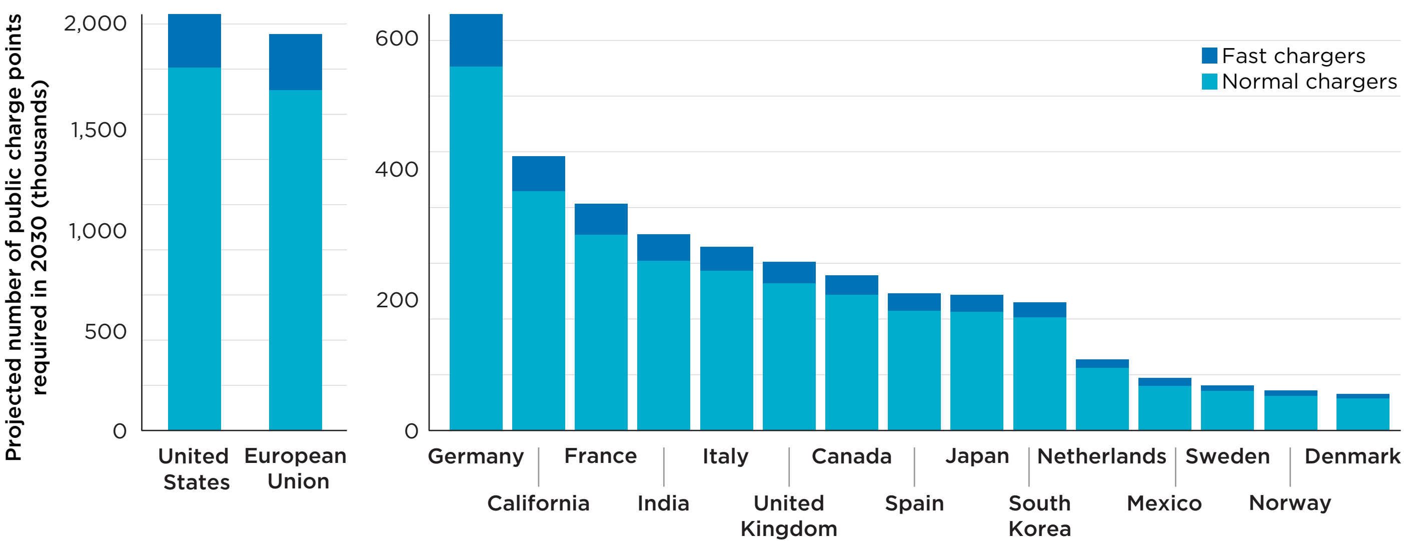

Figure 1. Projected number of public charge points needed for light-duty electric vehicles in 2030 for each ZEVTC member.

The 6 million public charge points required in 2030 can output a maximum of 170 GW. Spread out across 6 million vehicles, this is about 1.1 kW per electric vehicle, on average. This does not mean that 170 GW of additional publicly accessible power will be needed, as not all these chargers will be in use simultaneously and because a charger does not constantly deliver maximum power throughout a single charging session. Assuming chargers are used 20% of the time in 2030 and, on average, at slightly less than 70% of capacity, then only 21 GW of power generation (public power output capacity needed simultaneously) would be needed for LDVs in 2030.[7] That 21 GW is 0.6% of the power generation capacity of all ZEVTC members in 2021. While supply and demand cannot in practice be aggregated across ZEVTC members, as their power grids are not interconnected, the numbers are here to emphasize that the total installed power output is not equal to the power generation capacity required. As of mid-2022, 14% of the installed power output needed for public LDV charging in 2030 (170 GW) was already in place.

Our estimates of the need for charge points and installed power output vary by market because vehicle characteristics, vehicle use, and access to private charging vary. For example, while the European Union is estimated to have 72 million electric LDVs on its roads in 2030 and the United States is only projected to have 37 million, our modeling shows the United States will require more public chargers than the European Union. Additionally, the European Union will need 0.9 kW of installed public power output per electric vehicle, on average, in 2030 while the United States would need closer to 1.6 kW per vehicle. The difference is mainly because U.S. cars drive more miles and are less efficient than European cars on average, due to higher mass and relatively poor aerodynamics for some models. This means more energy is needed to power U.S. cars, and that requires more public charging installation. Even though North American drivers have more access to home charging than European and Asian drivers, this benefit is largely offset because they drive more miles with less-efficient vehicles.

Private charging needs, on the other hand, are more closely correlated with the number of electric vehicles on the road, as is clearly visible in Figure 2. As you can see, in 2030, the European Union is expected to need almost twice as many private LDV charge points as the United States and more than four times more than India. Setting aside the two largest markets, the European Union and the United States, Germany leads ZEVTC jurisdictions in terms of private charging needs as it is the largest electric vehicle market in 2030. By 2035, and as illustrated in Appendix B, Germany's needs are surpassed by those of India, because India is projected to have more electric vehicles on the road by then.

7 The 20% of the time means about 5 hours per day in 2030 and this comes from an assumed maximum utilization of 6 hours per day when mass electric vehicle adoption is reached. Marie Rajon Bernard and Dale Hall, "Assessing Charging Infrastructure Needs in Québec," (ICCT: Washington, D.C., 2022), https://theicct.org/publication/lvs-ci-quebec-can-en-feb22/. The 70% of capacity is related to the fact that at the beginning and the end of a charging session (when the battery is almost empty/full), the power delivered drops. Further, the power delivered is limited by the vehicle, so if the electric vehicle only accepts 50 kW but is plugged in to a 150 kW charger, then the power actually delivered will be maximum 50 kW (33% capacity in this case).

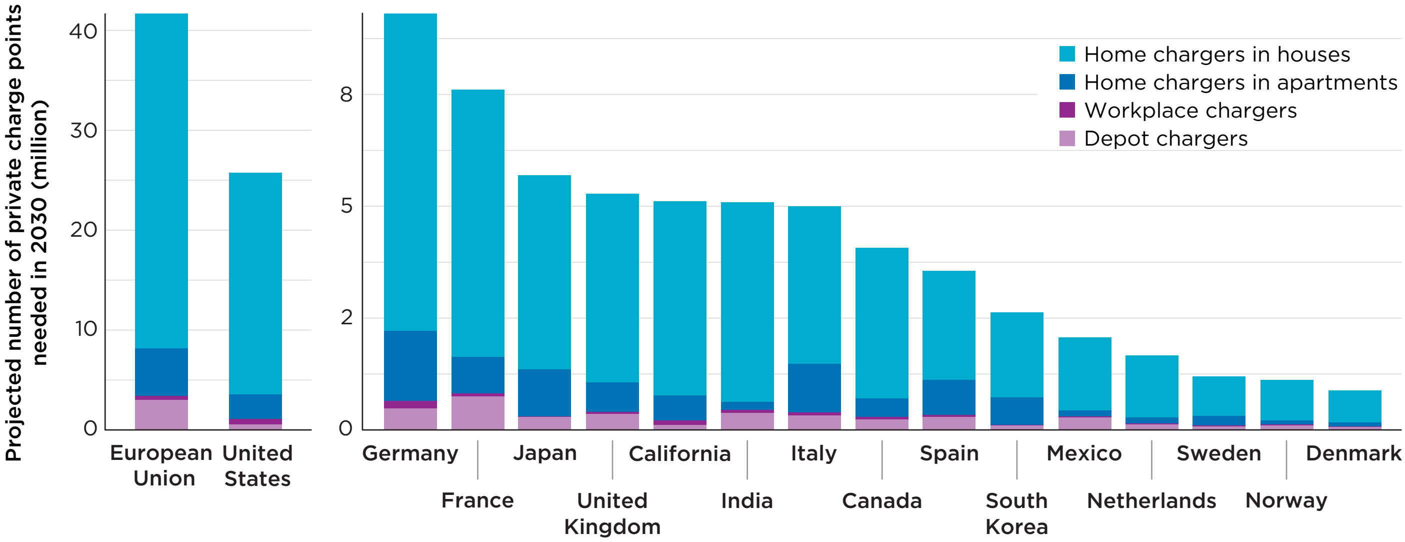

Figure 2. Number of private charge points needed for light-duty electric vehicles in 2030 for each ZEVTC member.

Governments should take note of housing stock and urban planning realities when planning. For example, Japan and most European countries will have a higher share of home chargers in multi-unit dwellings (apartments) than California, the United States as a whole, or Canada. This can be challenging because of the high upfront cost of installing chargers in apartments and because the division of responsibilities for the charger is sometimes unclear in apartment buildings. Some policies that can help overcome these challenges are discussed below.

Heavy-duty vehicles

There is essentially no public charging infrastructure in place for HDVs right now. Under an accelerated ZEV transition pathway, we expect that there will be nearly 3.1 million heavy-duty electric vehicles on the roads in ZEVTC jurisdictions in 2030.[8] The energy demand of battery-electric trucks is satisfied by three different types of direct current (DC) chargers. Overnight chargers, whether publicly accessible or at private locations such as depots and logistics hubs, delivering up to 100 kW; fast chargers delivering up to 350 kW; and ultra-fast chargers delivering up to 1 MW. While ultra-fast chargers could, in principle, deliver up to 3.75 MW, they are assumed to deliver a maximum of 1 MW in this study. We assume that it is most cost-effective for truck operators to maximize the use of overnight charging for two reasons: the hardware cost of overnight chargers is lower and charging at night offers access to cheaper electricity. Vehicles that return to their home depot every night, like urban and regional delivery trucks, will mostly rely on private overnight charging. Meanwhile, those not able to return, like long-haul trucks, will sometimes rely on public overnight charging. The share of private and public overnight charging in each jurisdiction thus depends on the number of long-haul trucks that typically do not return to their home depot every night. Still, overnight charging is not always sufficient, and heavily loaded trucks and trucks traveling long distances will have to recharge during the day using fast and ultra-fast charging.

8 Here, heavy-duty vehicles include medium- and heavy-duty trucks and buses with a gross vehicle weight above 3.5 tons. This paper will only present results for battery-electric heavy-duty vehicles; refueling infrastructure needs for fuel cell electric trucks will also be important to consider in government planning.

Our modeling shows that powering the nearly 3.1 million heavy-duty electric vehicles will require 200,000 public and 1.8 million private charge points. Figure 3 presents the total number of charge points needed in 2030 by ZEVTC jurisdiction. The figure does not display California, because our charging infrastructure assessment model was developed at the national level.

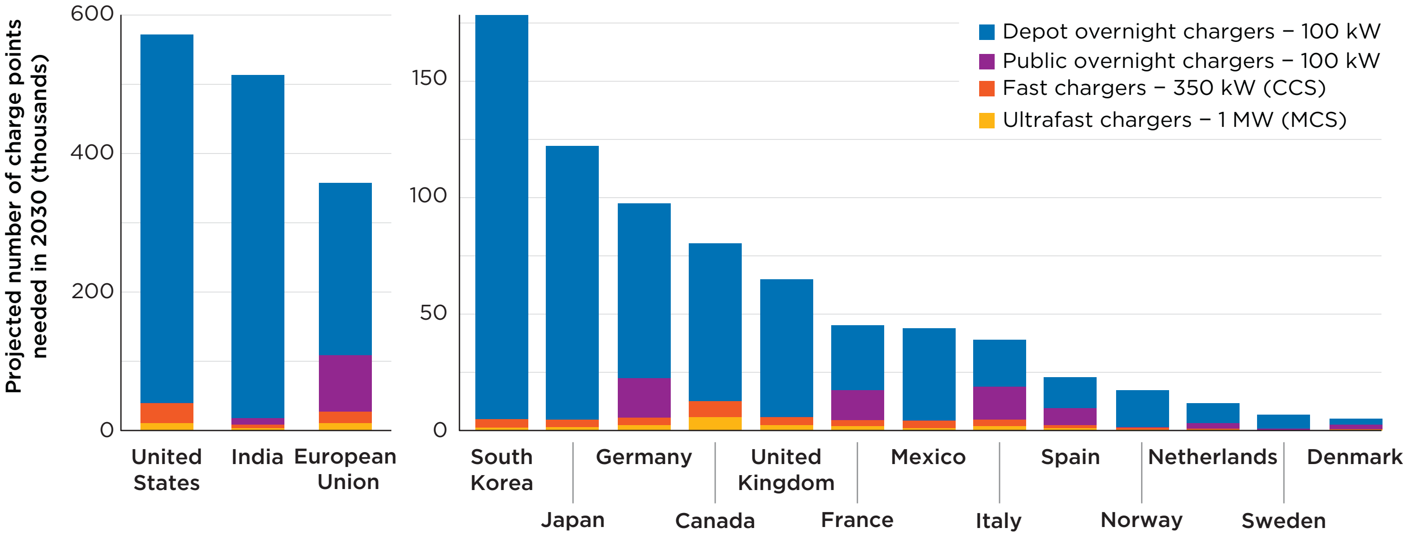

Figure 3. Number of charge points needed for heavy-duty electric vehicles in 2030 for each ZEVTC member.

With a projected 1 million heavy-duty electric vehicles on its roads in 2030, the United States is estimated to have the highest charging infrastructure needs, 570,000 chargers. India is second with a projected 700,000 electric HDVs in 2030 requiring 510,000 chargers, and the European Union is third, with a projected 760,000 electric HDVs requiring 360,000 chargers.

Notice how the European Union is estimated to have more electric HDVs than India but requires fewer total chargers. This is because its fleet is expected to have a higher number of long-haul electric trucks, and these are expected to rely more heavily on public overnight chargers and on a dense network of high-power chargers along European highways. While these high-power chargers can serve more trucks, they are also more expensive to install, and thus jurisdictions where these are installed might have higher costs than other markets, including those that require a larger total number of chargers.

The total number of HDV chargers that we project will be needed in 2030 will be able to output a maximum of 250 GW, around 70 GW of this public. Here, too, note that this does not mean that 250 GW of additional power output will be needed, because not all chargers will be used simultaneously and the chargers do not constantly deliver maximum power for the duration of any given charging session; additionally, some of them will use power sharing. In the United States, approximately 75 GW of installed power output is projected for 2030, 30% of which would be public. In the European Union, around 50 GW of installed power output will be needed in 2030, approximately half of it public. In India, 55 GW of installed power output will be needed in 2030, 11% of this public.

Pace

As presented in the previous section, ZEVTC members will need 6.2 million public chargers for light and heavy vehicles by 2030, and these would output a maximum of 240 GW. By mid-2022, ZEVTC members had only 13% of the public chargers needed and only 10% of the installed power output projected to be necessary for 2030.

Because the vast majority of the work still needs to be done, planning needs to start now to reach the level needed in 2030 and the charging network needs to grow substantially. Importantly, chargers cannot be deployed overnight: It usually takes between 2 months and 1 year[9] to deploy a normal charger and can take up to 10 years[10] to install a fast charger if grid upgrades are needed.

Figure 4 shows were each ZEVTC jurisdiction stands as of mid-2022 related to their 2030 charging needs. Green jurisdictions already have at least 25% of their 2030 public installed power output needs, yellow ones have between 10% and 25%, orange ones between 5% and 10%, and red ones less than 5%. Red jurisdictions (on the right) have further to go to reach the public charging infrastructure needs by 2030 while green ones (on the left) are closer.

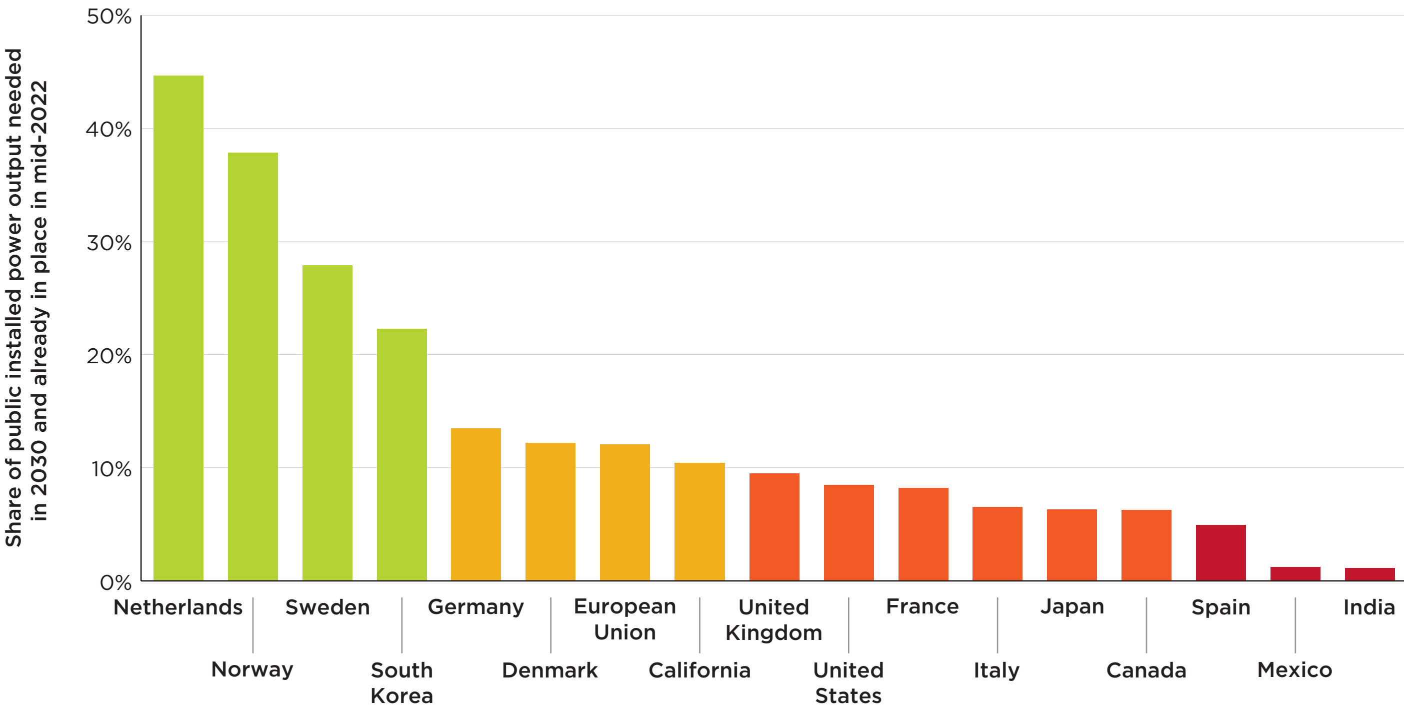

Figure 4. Share of projected public installed power output needed in 2030 that was already in place as of mid-2022.

9 Marie Rajon Bernard and Dale Hall, "Efficient Planning and Implementation of Public Chargers: Lessons Learned from European Cities," (ICCT: Washington, D.C., 2021), https://theicct.org/publication/efficient-planning-and-implementation-of-public-chargers-lessons-learned-from-european-cities/

10 Stein J. Brembu, "Kunnskapsgrunnlag om hurtigladeinfrastruktur for veitransport [Knowledge Base on Fast-Charging Infrastructure for Transport]," (The Norwegian Environment Agency and the Swedish Road Administration: 2022). https://www.regjeringen.no/contentassets/a07ef2d3142344989dfddc75f5a92365/kunnskapsgrunnlag_1mars.pdf

Speed at which jurisdictions need to grow their charging infrastructure network

Jurisdictions with a larger share of infrastructure already in place have the luxury of making up the remaining difference at a slower pace of growth. Still, the necessary charging infrastructure growth pace also depends on the speed at which electric vehicle sales are projected to ramp up.

For LDVs, our estimates of the year-on-year annual growth of public installed power output between mid-2022 and 2030 range from 7%–8% in the most EV-advanced ZEVTC jurisdictions of the Netherlands and Norway to over 50% for India and Mexico. For example, this means that India will have to multiply its installed public power output by 1.55 every year until 2030 while Norway will have to multiply it by 1.08. For HDVs, the same countries are at both ends of the spectrum with 26% yearly growth for Norway and 59% for India.

Figure 5 displays detailed results for every jurisdiction in terms of year-to-year public installed power output growth needed by 2030. No data are provided for California for HDVs since the model was developed at the country level. The colors correspond to how much the jurisdictions will have to grow their network each year. For LDVs, for a growth rate lower than 15% (i.e., a multiplication of the installed public power output by less than 1.15 per year), jurisdictions are in green. Jurisdictions that are between 15% and 25% are in yellow, between 25% and 30% are in orange, and above 30% are in red. For HDVs, the color bins are split at 30%, 45%, and 50%.

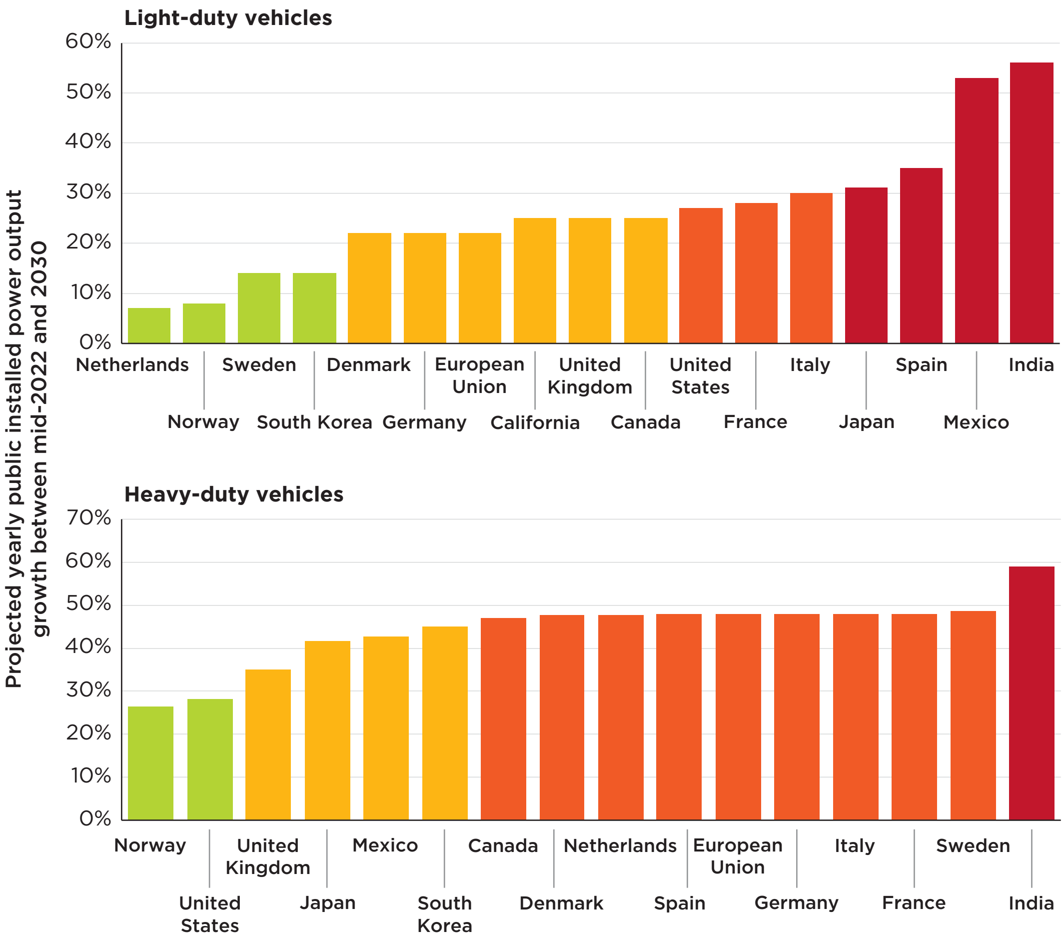

Figure 5. Projected year-to-year public installed power output growth for LDVs (top) and HDVs (bottom) between mid-2022 and 2030.

For LDVs, most markets are on track, and leading ones are even exceeding the required growth levels; however, markets further behind (in red) will need to speed up. For HDVs, almost no public charging has been deployed so far.

For private charging infrastructure, for LDVs we estimate a year-on-year growth ranging from 12% in Norway to 70% in India and for HDVs it ranges from 37% in the Netherlands to 82% in Italy. More details can be found in Appendix B.

Recall that we expect a later electrification of trucks, and especially long-haul trucks, in the United States, compared to Europe. That is why the needs for both public and private HDV charging growth are lower in the United States. Note, however, that a significant ramp-up in the United States is expected after 2030, primarily in public chargers used by long-haul trucks.

Cost

The scale of infrastructure described above will require significant investment. We estimate the cumulative public charging infrastructure investment for all ZEVTC jurisdictions between mid-2022 and the end of 2030 to be around €105 billion. While this is 0.2% of the sum of ZEVTC jurisdictions' GDP in 2021, experience shows these costs can be shared with the private sector. As for private charging, we estimate the cost by 2030 to be close to €230 billion. The majority of these costs should be covered by the private sector as they are for individual or corporate use. Still, targeted public subsidies might be needed in the short term for chargers in apartments, for example. These cost estimates include chargers' hardware, software, installation, and planning.[11] Additionally, these costs are based on 2021 as a reference year and do not account for inflation.

While total costs are substantial, they are vastly outweighed by the societal benefits from electric vehicles.[12] These benefits will only grow as the ZEV market grows. Conversely, if the market is obstructed by lack of infrastructure, the benefits will not accrue. Moreover, it has been shown that investing in charging infrastructure is four to seven times more cost-effective than providing electric vehicle subsidies and builds confidence in ZEVs.[13]

Although public investments are crucial in the short term, this is not expected to persist indefinitely. Indeed, most public chargers installed in leading markets like Norway and the Netherlands are already being built today with no public funding support, thanks to high utilization and strong vehicle electrification policies that give confidence to the private sector.[14] Additionally, estimates done for the European Commission's Alternative Fuel Infrastructure Regulation (AFIR) proposal suggest that 40% of LDV and 50% of HDV charging infrastructure costs will be supported

11 Grid upgrade costs are not included, due to too much uncertainty and variation in local conditions. Nonetheless, some more information on this will be included in an upcoming ICCT paper. Marie Rajon Bernard et al., "Charging Solutions for Battery-Electric Trucks," (ICCT: Washington, D.C., in press).

12 Slowik et al., "Funding the Transition."

13 Vivien Foster et al., "If You Build It, They Will Come: Lessons From the First Decade of Electric Vehicles," *World Bank Blogs*, December 20, 2021, https://blogs.worldbank.org/transport/if-you-build-it-they-will-come-lessons-first-decade-electric-vehicles.

14 Esther van Bergen et al., "Policies for a mature, flourishing equitable EV charging ecosystem," (GSMP: Leicestershire, U.K., 2021), https://zevalliance.org/mature-ev-charging-ecosystem-nov21/

by public funds up to 2030, and both decline to 10% thereafter.[15] Note that this is an estimate and might only apply to European jurisdictions.

Based on the charging infrastructure modeling and cost assumptions in Appendix A, Figure 6 presents the split of this cost by charging categories and provides information for the three largest ZEVTC markets.

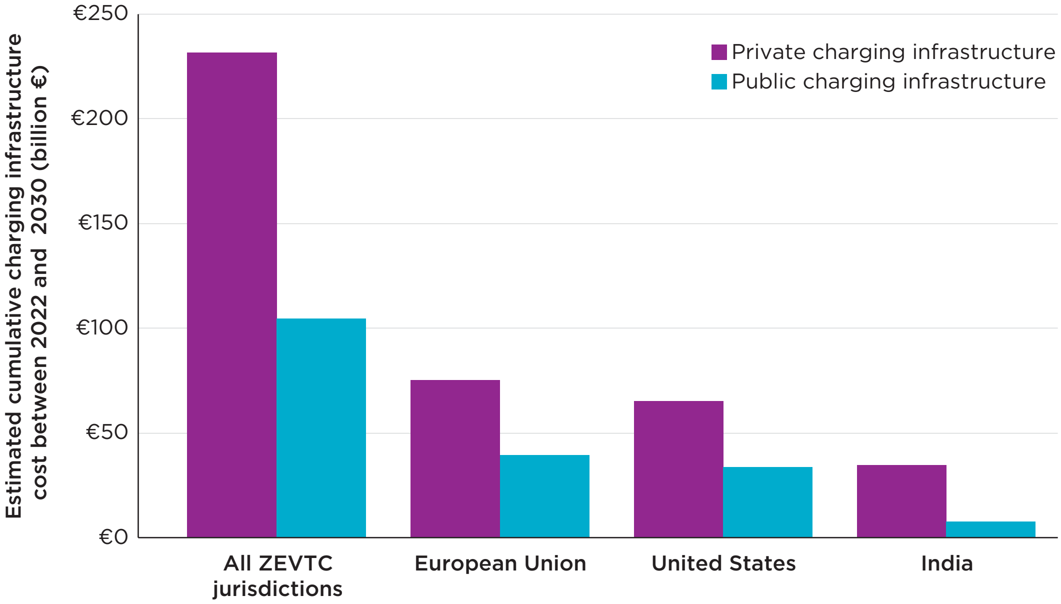

Figure 6. Estimated cumulative charging infrastructure cost between 2022 and 2030 for all ZEVTC jurisdictions, the European Union, the United States, and India.

Even though not shown in this graph, EU and U.S. costs are dominated by LDV infrastructure (76% and 59% of their total costs, respectively), while India's charging infrastructure costs are dominated by HDV infrastructure (71% of the total). Because of later electrification in the HDV segment, HDVs' share of total costs will be higher by 2035 for the European Union and the United States. HDV infrastructure costs represent 24% of the total costs in the European Union in 2030, and that rises to 49% in 2035.

Policies for promoting infrastructure build-out

Infrastructure projects can take years to plan and build, and governments must act now if charging infrastructure is to scale up in time to meet future ZEV demand. Infrastructure planning requires coordination between governments and transport, energy, and infrastructure providers, and targeted regulations and public grants could address the gaps in charging networks and support more equitable outcomes. Governments can limit public funding by supporting new business models that would help the private sector take on more of the costs over time.

While there is no universal approach to designing an infrastructure plan, we reviewed policies developed by ZEVTC members to address key challenges. These are based on

15 European Commission, "Proposal for a Regulation of the European Parliament and of the Council on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU of the European Parliament and of the Council," July 14, 2021, https://ec.europa.eu/info/sites/default/files/revision_of_the_directive_on_deployment_of_the_alternative_fuels_infrastructure_with_annex_0.pdf

a decade of experience in leading markets, and we find three key themes for boosting infrastructure deployment: *binding infrastructure targets* aligned with ZEV sales goals; supportive *regulatory tools and targeted incentives* to attract private capital and achieve equitable outcomes; and *future-proofing the grid* through new utility models and smart charging.

Infrastructure planning and coordination

Planning for infrastructure is crucial. Governments like Germany and the United Kingdom are developing national-level roadmaps for charging that are intended to result in a robust network with broad geographic coverage and power capacity that is adequate for meeting vehicle sales goals. Binding installation targets in particular provide greater legal certainty for all participants because there is some mechanism for enforcement. Such targets are also expected to encourage investment in the new market, as history has shown that private-sector actors strongly prefer policy certainty. Multiple stakeholders need to be involved in charging infrastructure planning. This requires breaking the silos between agencies of energy, transportation, and environment and coordinating with electricity utilities to streamline policy implementation and ensure smooth and efficient charging infrastructure rollout.

Build market confidence by setting binding installation targets for charging infrastructure that comports with the ZEV sales targets set by ZEVTC governments. Targets that include a mechanism for ensuring compliance reflect a stable and sure policy vision and send a clear signal to businesses and investors about both the direction of the market and the plan for growing infrastructure investments over time.

The European Commission proposed the aforementioned AFIR in July 2021, and if adopted, it will be the first binding regulation related to public charging at the EU level. In the light-duty segment, member states would be required under AFIR to provide 1 kW of installed public power output per battery electric vehicle and 0.66 kW for each plug-in hybrid electric vehicle at the end of each calendar year. For HDVs, the AFIR proposal includes a target of one electric vehicle charging area per direction every 60 km along the core Trans-European Network for Transport (TEN-T), with each area having at least 1,400 kW of power output by 2025 and 3,500 kW by 2030.[16] It also includes power output targets to serve trucks along the long-haul EU traffic corridors and urban nodes, and a dedicated, secure parking area. Considering there have been differences in policy ambition and uneven uptake of charging infrastructure among the 27 EU members, the introduction of mandatory minimum targets and harmonized requirements is meant to help promote the installation of a robust network across Europe.[17] Under AFIR, member states are to develop nationally binding policy frameworks that detail tailored infrastructure rollout plans and strategies and infrastructure providers are to provide data to member states to allow for compliance monitoring and enforcement.

While the LDV part of the AFIR regulation is likely to be sufficient for many jurisdictions in the long term, as long as there are changes based on regulatory context, we suggest a stepwise approach with higher short-term targets based on the electric vehicle stock

16 The Core TEN-T network encompasses the main long-haul traffic roads in the European Union. The Comprehensive TEN-T network is composed of all the long-haul traffic corridors of the EU.

17 Transport and Environment, "AFIR: Providing Infrastructure to Make Transport Fit for 55," (Brussels, November 2021), https://www.transportenvironment.org/wp-content/uploads/2021/11/20211004_AFIR_Briefing.pdf.

share.[18] For jurisdictions interested in this approach, more details are in Appendix B. For the HDV segment, the European Union is also considering adapting the TEN-T network power output targets to the expected traffic flow volumes in different sections of the European road network.[19] Sections of traffic corridors with a low number of trucks per day could install charging areas with lower total installed power output.

In January 2022, the Government of India amended its guidelines and standards for charging infrastructure for electric vehicles by setting certain requirements for installations and electricity rates for public chargers.[20] The guidelines target one public charging station per 100 km on highways for HDVs by 2025; each station is to have at least two public chargers with over 100 kW power output and must be located in an area that is at least 15 m x 7 m to accommodate large heavy-duty trucks and buses.

Supporting regulations and incentives

Starting from the early stages of infrastructure planning, governments have many options for addressing charging gaps. Gaps are areas where there are relatively fewer chargers, including where there are not enough chargers to meet forecasted demand and areas lacking chargers due to geographic or demographic attributes. Government tools include regulatory and financial incentives for developing charger networks in underserved areas and public-private funding models to spur new business models for early-stage charging technologies. In addition, governments can help remove barriers to infrastructure rollout by imposing equity mandates on utility investments and setting electric vehicle-ready building codes. As new business models develop, governments can phase out subsidies and transfer the cost of infrastructure build-out to the private sector over time.

Craft equity-centered programs to help ensure charging access in underserved areas, including rural and disadvantaged communities with limited access to public chargers. Studies show that low-income neighborhoods and communities of color have considerably lower electric vehicle ownership and less access to chargers, despite being exposed to higher levels of air pollution from road vehicles.[21] To address this, incentive programs targeting disadvantaged and rural communities must be incorporated into infrastructure plans.

Part of the U.S. Infrastructure Investment and Jobs Act is $2.5 billion in public grants to support alternative fuel corridors and community charging that would increase charging access for underserved and overburdened communities.[22] Additionally, the U.S. National Electric Vehicle Infrastructure (NEVI) funding program will distribute

18 Marion Rajon Bernard et al., "A Review of the AFIR Proposal: How Much Power Output Is Needed for Public Charging Infrastructure in the European Union?," (ICCT: Washington, D.C., 2022), https://theicct.org/wp-content/uploads/2022/03/europe-ldv-review-of-afir-proposal-how-much-power-output-needed-for-public-charging-infrastructure-in-the-eu-mar22-2.pdf.

19 Pierre-Louis Ragon et al., "A Review of the AFIR Proposal: Public Infrastructure Needs to Support the Transition to a Zero-Emission Truck Fleet in the European Union," (ICCT: Washington, D.C., 2022), https://theicct.org/publication/afir-eu-hdv-infrastructure-mar22/.

20 Government of India, Ministry of Power, "Charging Infrastructure for Electric Vehicles – The Revised Consolidated Guidelines and Standards," (New Delhi, 2022), https://powermin.gov.in/sites/default/files/webform/notices/Final_Consolidated_EVCI_Guidelines_January_2022_with_ANNEXURES.pdf.

21 Chih-Wei Hsu and Kevin Fingerman, "Public Electric Vehicle Charger Access Disparities across Race and Income in California," *Transport Policy*, (January 2021): 59–67. and Maria Xylia and Somya Joshi, "A Three-Dimensional View of Charging Infrastructure Equity," (Stockholm Environment Institute: Stockholm, Sweden, 2022), https://cdn.sei.org/wp-content/uploads/2022/06/3d-charging-infrastructure-sei2022.020.pdf.

22 The White House, "Fact Sheet: The Bipartisan Infrastructure Deal," November 6, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.

$5 billion for a nationwide charging network, and states are required to implement community outreach programs.[23] The California Energy Commission also approved a 3-year, $1.4 billion charging infrastructure plan with half the funds earmarked for disadvantaged communities.[24] The plan will increase the budget of the California Electric Vehicle Infrastructure Project (CALeVIP), one of the incentive programs to address equity-based charging gaps.

Many U.S. states require utilities to incorporate equity in charging investments, and California and New York are leaders.[25] The New York Public Service Commission ruled that utilities must consider environmental justice communities in charging investments.[26] Approved in September 2020, California's Assembly Bill 841 requires that at least 35% of utility investments be in underserved communities.[27] As of November 2021, U.S.-based utilities had announced $775 million for transportation electrification in underserved communities, equivalent to 23% of the total $3.3 billion.[28]

Set electric vehicle-ready building codes to promote charging at home and work. Accommodating the charging needs of electric vehicles will require updating the electric wiring in residential and commercial buildings, and retrofitting existing buildings is more expensive than new construction.[29] Governments can adopt more stringent electric vehicle-ready building codes for new construction and major renovations to support charging. One example of electric vehicle-ready building codes is from the United Kingdom, where the national government announced a new mandate requiring all new buildings and those undergoing major renovations in England to install electric vehicle chargers starting in 2022. That is expected to add 145,000 charge points across England each year until 2030.[30] Additionally, the European Commission proposal for the Energy Performance of Buildings Directive includes a requirement that new residential and non-residential buildings install pre-cabling for parking spaces.[31]

Leverage financial incentives to accelerate private charger installations in multi-unit dwellings. Many electric vehicle drivers will rely on private charging at home and the workplace, as these are more convenient and cheaper than public chargers. But those

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23 The U.S. Department of Transportation, "The National Electric Vehicle Infrastructure Formula Program Guidance," February 10, 2022, https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf.

24 California Energy Commission, "CEC Approves $1.4 Billion Plan for Zero-Emission Transportation Infrastructure and Manufacturing," news release, November 15, 2022, https://www.energy.ca.gov/news/2021-11/cec-approves-14-billion-plan-zero-emission-transportation-infrastructure-and.

25 Peter Huether, "Siting Electric Vehicle Supply Equipment (EVSE) with Equity in Mind," (ACEEE: Washington, D.C., 2021), https://www.aceee.org/sites/default/files/pdfs/siting_evse_with_equity_final_3-30-21.pdf.

26 New York Department of Public Service, "Proceeding on Motion of the Commission Regarding Electric Vehicle Supply Equipment and Infrastructure," Pub. L. No. CASE 18-E-0138 (2020), https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={6238DD07-3974-4C4E-9201-3E339E311916}.

27 State of California, "Assembly Bill No 841," (2020), https://leginfo.legislature.ca.gov/faces/billPdf.xhtml?bill_id=201920200AB841&version=20190AB84190CHP.

28 Nicole Lepre, "23 Percent of Utility Funding for Electric Vehicles Targeted for Underserved Communities," Atlas EV Hub, January 28, 2022, https://www.atlasevhub.com/data_story/23-percent-of-utility-funding-for-electric-vehicles-targeted-for-underserved-communities/?utm_source=EV+Hub&utm_campaign=2e554d9b56-EMAIL_CAMPAIGN_2019_01_07_05_37_COPY_01&utm_medium=email&utm_term=0_173e047b1f-2e554d9b56-244364665.

29 Pacific Northwest National Laboratory, "Electric Vehicle Charging for Residential and Commercial Energy Codes," (Richland, Washington, 2021), https://www.energycodes.gov/sites/default/files/2021-07/TechBrief_EV_Charging_July2021.pdf.

30 The U.K. Prime Minister's Office, "PM to Announce Electric Vehicle Revolution," news release, November 21, 2021, https://www.gov.uk/government/news/pm-to-announce-electric-vehicle-revolution.

31 The European Commission, "Proposal for a Directive on the Energy Performance of Buildings," December 15, 2021, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889.

who rent their homes are less likely to invest in charger equipment because they are somewhat likely to move in the future, and owners of multi-unit dwellings might not see a business case for installing charging to attract tenants.[32]

The United Kingdom's electric vehicle charge point grants scheme provides up to 75% of the purchase and installation costs of a charger for renters and landlords, capped at £350.[33] In addition, multi-unit building owners can apply for £30,000 per building, up to 30 applications per year. Canada's C$680 million Zero Emission Vehicle Infrastructure Program targets charging infrastructure deployment in multi-unit residential buildings.[34] In 2022, the program approved C$899,000 in funding for Broadstreet Properties to build Level 2 chargers across the country, and this financed almost half of the total project cost.[35]

California's Alameda County Incentive Project covers up to 75% of the hardware and installation costs of Level 2 and DC fast chargers, and targets at least half of this funding to be invested in multi-unit dwellings.[36] The project, co-funded by California Energy Commission and East Bay Community Energy, aims to install these chargers primarily in disadvantaged and low-income neighborhoods with an additional $500 per connector. Considering over half of the residents living in rented apartment buildings or multi-unit dwellings are low-income households in the United States, access to private charging at residential rates can lower the cost of owning an electric vehicle.[37]

Implement financial incentives to accelerate heavy-duty vehicle charging. In this segment, charging is still in the early stages of development and is led mainly by the United States and Europe. Government subsidies often come in the form of tax credits, rebates, and public grants, and these are intended to foster private investment. France introduced a subsidy for installing private chargers for heavy-duty fleets under the Advenir program.[38] The subsidy will cover up to 60% of the cost of a charge point in a private parking lot. For chargers with a power output above 500 kW, this program finances up to €960,000 toward grid connection costs in each depot. Germany announced €5 billion for building charging and refueling infrastructure for commercial cars and trucks until 2024 and will cover up to 80% of total project costs.[39]

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32 Ethan Elkind et al., "Driving Equity: Policy Solutions to Accelerate Electric Vehicle Adoption in Lower-Income Communities," (Berkeley Center for Law, Energy and the Environment: Berkeley, California, 2022), https://www.law.berkeley.edu/wp-content/uploads/2022/04/Driving-Equity-May-2022.pdf.

33 The U.K. Office of Zero Emission Vehicles, "EV Chargepoint Grant for Flat Owner-Occupiers and People Living in Rented Properties: Customer Guidance," updated August 4, 2022, https://www.gov.uk/government/publications/ev-chargepoint-grant-for-flat-owner-occupiers-and-people-living-in-rented-properties-customer-guidance/ev-chargepoint-grant-for-flat-owner-occupiers-and-people-living-in-rented-properties-customer-guidance.

34 Government of Canada, "Zero Emission Vehicle Infrastructure Program," accessed June 15, 2022, https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/zero-emission-vehicle-infrastructure-program/21876.

35 Government of Canada, "New EV Chargers Coming to Multi-Unit Residential Buildings Across Canada," news release, May 2, 2022, https://www.canada.ca/en/natural-resources-canada/news/2022/04/new-ev-chargers-coming-to-multi-unit-residential-buildings-across-canada.html.

36 CAleVIP, "Alameda County Incentive Project," accessed August 9, 2022, https://calevip.org/incentive-project/alameda-county.

37 Huether, "Siting Electric Vehicle Supply Equipment (EVSE) with Equity in Mind."

38 Advenir, "Une Nouvelle Prime à Destination des Flottes de Véhicules Poids Lourds Vient Enrichir Le Programme ADVENIR," May 4, 2021, https://advenir.mobi/2021/05/03/nouvelle-prime-flottes-poids-lourds/.

39 German Ministry for Transport and Digital Infrastructure, "Richtlinie Über Die Förderung von Leichten Und Schweren Nutzfahrzeugen Mit Alternativen, Klimaschonenden Antrieben Und Dazugehöriger Tank- Und Ladeinfrastruktur," (2021), https://www.klimafreundliche-nutzfahrzeuge.de/wp-content/uploads/2021/08/Foerderrichtlinie.pdf.

Public-private partnerships are emerging as a good model for achieving economies of scale in heavy-duty charging. Pilot projects such as Electric Island in Portland, a joint initiative of Daimler Trucks and Portland General Electric, are studying energy management, charger usage, and heavy-duty vehicle performance and can help understand energy management and charger utilization.[40] Additionally, HoLa in Germany[41] is testing out megawatt chargers and Volvo LIGHTS in California is generating knowledge about the optimization of charging logistics[42] and the benefits of smart charging.[43] All of this is crucial to developing best practices and bringing the private sector on board.[44]

Improving grid resilience

Traditional regulatory models incentivize utilities to keep costs low for all customers and were designed to deliver electricity to buildings. Such models are less able to proactively meet the requirements of charging mobile electric vehicles. Governments need to future-proof the grid to accommodate growing electricity demand from ZEVs and they need to start now because grid upgrades can take up to 10 years. Supportive policies include deploying utility ratepayer programs to generate revenues from electric vehicle charging and smart charging to avoid costly upgrades.

Empower utilities to build out grid infrastructure for electric vehicles to reduce overall costs through scale. Regulators can enable utilities to invest in needed upgrades ahead of the power demand from electric vehicles. In 2021, the California Public Utilities Commission approved new rules for investor-owned utilities to provide charging infrastructure and cover the utility-side distribution system upgrade costs through increased electricity rates over time.[45] The new tariffs will reduce the total cost of charging installations by approximately 25%, according to NRDC.[46] In 2018, the Quebec government revised its energy management law by setting new charging rates for consumers because the existing public-private cost-sharing model was not profitable enough to deploy fast chargers at a pace needed to meet the growing ZEV demand.[47] With this law, Hydro-Quebec can redirect revenues from electricity sold through home charging to install fast chargers while limiting overall customer electricity price increases.

40 Dalmier Trucks, "Daimler Trucks North America, Portland General Electric open First-of-its-kind heavy-duty electric truck charging site," news release, April 24, 2021, https://northamerica.daimlertruck.com/PressDetail/daimler-trucks-north-america-portland-general-2021-04-21

41 MAN Truck and Bus, "MAN and ABB E-Mobility Rev up for the Next Phase of Electromobility in Long-Haul Trucking," news release, May 13, 2022, https://press.mantruckandbus.com/corporate/man-and-abb-e-mobility-rev-up-for-the-next-phase-of-electromobility-in-long-haul-trucking/

42 Volvo Lights, "Project Map," accessed August 9, 2022, https://www.lightsproject.com/project-map/

43 Volvo Lights, "About Volvo LIGHTS," accessed August 9, 2022, https://www.lightsproject.com/about/

44 Marie Rajon Bernard et al., "Charging Solutions for Battery-Electric Trucks."

45 Public Utilities Commission of the State of California, "Resolution E-5167 Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric Request Approval to Establish New Electric Vehicle (EV) Infrastructure Rules and Associated Memorandum Accounts, Pursuant to Assembly Bill 841," (2021), https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M413/K061/413061495.PDF.

46 Miles Miller and Max Baumhefner, "CA Approves New Rules to Support EV Charging Infrastructure," NRDC, October 8, 2021, https://www.nrdc.org/experts/miles-muller/ca-approves-new-rules-support-ev-charging-infrastructure.

47 Quebec National Assembly, "An Act to Promote the Establishment of a Public Fast-Charging Service for Electric Vehicles," Bill 184 § chapter 25 (2018), http://www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=5&file=2018C25A.PDF.

Require smart charging capability because it balances the grid load and could potentially defer expensive grid upgrades.[48] In December 2021, the United Kingdom passed the Electric Vehicles Smart Charge Points Regulation, which requires all new home and workplace chargers to be smart chargers from June 30, 2022 onward.[49] New chargers can be switched off during peak electricity demand hours and can delay charging at other times. The Netherlands announced a temporary incentive program, Smart Charging for Everyone, and its goal is smart chargers for 70% of electric car drivers by 2025.[50] This is a multistakeholder program with car manufacturers, national and local governments, and charging network operators.[51]

Summary of policies

Sustained policy support drives charging deployment in leading ZEVTC members. Table 1 showcases strong infrastructure policies, including installation targets, incentives, and planning for grid resilience. Governments can reserve public funds for addressing charging gaps and difficult applications that include cost-sharing provisions with the private sector. As the ZEV market grows over the next decade, governments can share best practices and adjust their policies.

Table 1. Summary of policy options for charging infrastructure build-out

Policy area	Policy tools	Examples
Installation targets and standards	Binding capacity and distance-based targets	**EU AFIR proposal:** 1 kW per battery electric vehicle and 0.66 kW for plug-in hybrid for LDVs, and at least 3,500 kW per charging pool for HDVs every 60 km per direction by 2030 on the core road network
	Charging standards	**India:** Charging standards for LDVs and HDVs, limits set on the electricity rates, requirements for power output and location
Regulations and incentives	Equity-centered mandate	**California:** At least 35% of utility investments in underserved communities
	Electric vehicle-ready building codes	**United Kingdom:** All new or significantly renovated residential and non-residential buildings with associated parking to install EV chargers from 2022
	Multi-unit dwelling public grants	**Canada:** Cost-sharing with real estate developers to install charging in multi-unit dwellings
	HDV public grants	**Germany:** Up to 80% of project cost of private charging for heavy-duty commercial vehicles
Grid resilience	Smart charging incentive	**Netherlands:** Smart chargers for 70% of electric vehicle users by 2025
	Smart charging mandate	**United Kingdom.:** All new home and workplace chargers to be smart chargers from June 2022
	Electric vehicle-friendly rate structures	**Quebec:** Public utility can subsidize fast charger installations through new electricity pricing schemes for electric vehicle home charging

48 Jaap Burger et al., "The Time Is Now: Smart Charging of Electric Vehicles" (Regulatory Assistance Project: Brussels, Belgium, 2022), https://www.raponline.org/wp-content/uploads/2022/04/rap-jb-jh-smart-charging-europe-2022-april-26.pdf.

49 The U.K. Government, "The Electric Vehicles (Smart Charge Points) Regulations 2021," (2021), https://www.legislation.gov.uk/uksi/2021/1467/contents/made.

50 The Nationale Agenda Laadinfrastructuur, "Vooraankondiging Marktconsultatie Programma 'Slim Laden Voor Iedereen,'" February 9, 2022, https://www.agendalaadinfrastructuur.nl/nieuws/2152576.aspx?t=Vooraankondiging-marktconsultatie-programma-%e2%80%98Slim-laden-voor-iedereen%e2%80%99.

51 The Nationale Agenda Laadinfrastuctuur, "Smart Charging Requirements," December 8, 2021, https://agendalaadinfrastructuur.nl/ondersteuning+gemeenten/documenten+en+links/documenten+in+bibliotheek/handlerdownloadfiles.ashx?idnv=2108316.

Appendix A. Charging infrastructure modeling

Light-duty vehicles

An overview of the modeling approach for light-duty vehicles (LDVs) charging infrastructure needs is presented in Figure A1 and more details can be found in previous ICCT analysis.[52] The light blue rectangles are the data inputs for each step, and each step is represented by the dark blue rectangles.

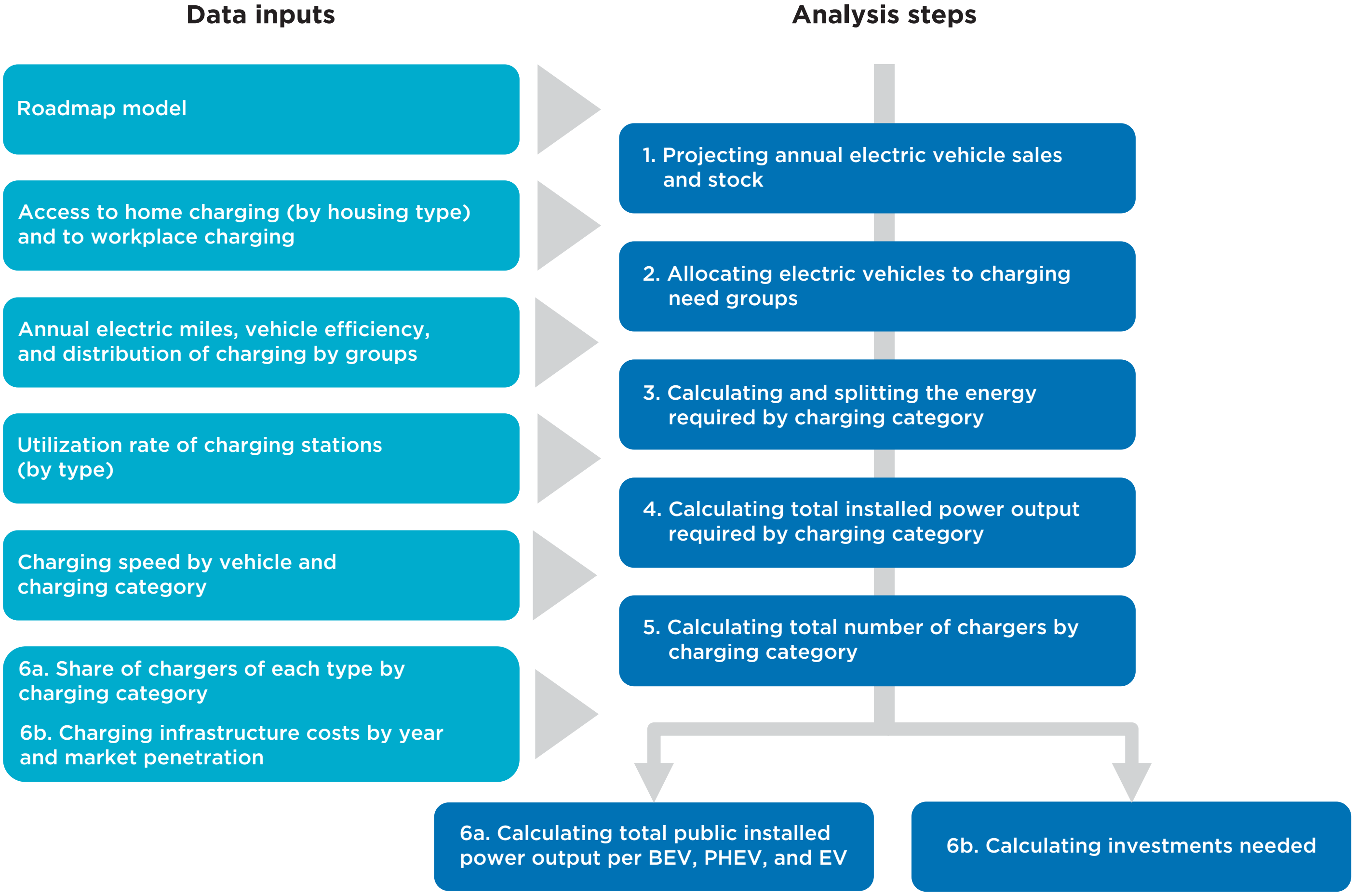

Figure A1. Charging infrastructure modeling for light-duty vehicles.

The model starts with the projection of annual electric vehicle sales, and this allows us to track battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) stock over time based on a stock turnover model. This projection follows the Ambitious scenario of the ICCT's Roadmap model, which assumes full zero-emission LDV sales in Norway in 2025, in European Union countries in 2030, in the United Kingdom, California, and Canada in 2035, and in the United States, Mexico, Japan, South Korea, and India in 2040.

The next step allocates this vehicle stock to driver groups depending on the type of car (BEV vs. PHEV), home charging availability, commuting status (car commuter vs. non-car commuter), workplace charging availability, and depot charging availability

52 Marie Rajon Bernard et al., "Charging Infrastructure to Support the Electric Mobility Transition in France," (ICCT: Washington, D.C., 2021), https://theicct.org/publication/charging-infrastructure-to-support-the-electric-mobility-transition-%E2%80%AFin-france%E2%80%AF/.

for light-commercial vehicles. For home charging availability, dwelling type is used as a proxy: Electric vehicle owners living in houses are more likely to have access to home charging than those living in apartments.

After this, in Step 3, the daily energy required is forecasted for each charging group based on mileage and vehicle efficiency. Vehicle efficiency is expected to stay constant throughout the years as technology improvements are assumed to be counterbalanced by an increase in vehicle mass. This electricity demand is then split per charging setting (home, workplace, depot, public normal, public fast in urban settings, and public fast along major roads). The share of energy delivered through each charging setting depends on the charging group.

Steps 4 and 5 translate this electricity into the number of chargers required based on estimated daily charger utilization (in hours) and vehicle charging speed (in kW). For public chargers, we assume a logarithmic increase of active utilization, as a function of electric vehicle stock share, until a maximum of 6 hours per day. For workplace chargers we assume a constant utilization of 5 hours per workday. For fast chargers along road corridors, a different methodology is used. The total number of chargers needed is directly correlated to the BEV stock of each jurisdiction. Indeed, the number of corridor chargers needed depends less on the annual energy they need to deliver than on the vehicle throughput on high-activity days such as holidays and weekends.

A different methodology is also used for private chargers. For chargers in houses, there is one home charger per BEV with access to home charging and slightly less than one charger per PHEV, assuming that PHEVs sometime share chargers with another electric vehicle. For chargers in apartments, there is one home charger per 2 electric vehicles. Finally, for depot chargers, there is 1 charger for 2.5 BEVs (assuming that BEVs charge 3 nights per week) and 1 charger for 4.5 PHEVs (assuming that PHEVs charge 1.5 nights per week or that they share a charger with another PHEV 3 nights per week). Charger sharing can be done through entire-site power-sharing among multiple charging ports, power sharing through multiple charging ports on one charger, or physically moving a port from one car to another.

After obtaining the total number of chargers, two additional steps can be taken. For the first additional step (6a.), the total public power output is estimated based on the number of chargers in each public charging setting and on assumptions related to the rated power output of these chargers; the result is then divided by the electric vehicle stock from Step 1. Overall, there is an assumed increase in chargers' rated power output for all public charging categories (normal, fast urban, fast along road corridors). This is based on the improvement of vehicle charging acceptance rate, high-power charger technology, and public charging operators' tendency to deploy higher power chargers, especially DC fast chargers.

For the second additional step (6b.), the total cost of both public and private charging infrastructure is estimated based on charging infrastructure capital and operational cost estimates. For capital costs, only hardware, software, planning, and installation costs are considered. Grid connection and upgrade costs are not estimated due to high uncertainty, lack of data, and high variation depending on the local context. Operational costs are calculated as a share of hardware and software costs in 2022. A learning rate of 2% is assumed for all the costs. Learning rates describe how the cost of a technology or work decreases as the cumulative output increases, as a result of learning by doing and economies of scale. Due to a lack of specific data, charger costs are assumed to be the same for all jurisdictions.

Table A1. Charging infrastructure cost estimates for 2022.

Type	Capacity (kW)	Hardware	Installation	Planning	Operation and maintenance (per year, share of hardware and software costs)
Home		€ 600	€ 1,000		
Apartment		€ 600	€ 1,125		
Workplace	7.4 or 11	€ 1,320	€ 1,240	€ 560	1.4%
Public normal	7.4	€ 670	€ 750	€ 450	1.6%
	11	€ 1,970	€ 1,725	€ 675	1.4%
	22	€ 3,280	€ 2,700	€ 900	1.2%
Public fast and ultra-fast	50	€ 28,125	€ 15,190	€ 1,350	1.2%
	150	€ 70,000	€ 18,000	€ 3,645	1.2%
	350	€ 170,000	€ 54,000	€ 7,655	1.2%
	1000	€ 437,140	€ 154,290	€ 21,870	1.2%

Heavy-duty vehicles

The level of infrastructure rollout required to support the electrification of heavy-duty trucks and buses is heavily dependent on vehicle activity and charging strategies. These are expected to vary widely across vehicle segments, industry sectors, and jurisdictions. We therefore developed assumptions for each vehicle segment and jurisdiction based on the most representative vehicle activity taken from limited real-world data and on charging strategy, and we balanced the use of different types of chargers. The full methodology and key assumptions are outlined in a recent ICCT study.[53]

The fleet's energy needs are modeled using ICCT's Roadmap model. Projections for the uptake of zero-emission HDVs are aligned with the ICCT's Ambitious scenario, which assumes an accelerated and widespread transition to ZEVs in ZEVTC countries and China.[54] The Ambitious scenario results in a 2030 ZEV sales share of 40% to 50% for medium trucks, 30% to 40% for heavy trucks, and 75% to 90% for buses. For the United States, we use ICCT's recommendations for the new Environmental Protection Agency HDV rulemaking, which builds on manufacturer ambitions and existing legislation in California and several other states and extends it to the national level.[55] Finally, for the European Union, we use a scenario aligned with European manufacturers' announcements on the sales of "fossil-free" vehicles through 2040, which closely align the sector with the Paris Agreement. This scenario results in a 60% reduction in CO_2 emissions from new HDVs in 2030, a 90% reduction in 2035, and a 100% reduction in 2040.[56] Both the U.S. and EU scenarios are aligned with the

53 Pierre-Louis Ragon et al., "A Review of the AFIR Proposal: Public Infrastructure Needs to Support the Transition to a Zero-Emission Truck Fleet in the European Union," (ICCT: Washington, D.C., 2022), https://theicct.org/publication/afir-eu-hdv-infrastructure-mar22/

54 Arijit Sen and Joshua Miller, "Emissions Reduction Benefits of a Faster, Global Transition to Zero-Emission Vehicles," (ICCT: Washington, D.C., 2022), https://theicct.org/publication/zevs-global-transition-benefits-mar22/.

55 International Council on Clean Transportation, "ICCT Comments on EPA Proposed HDV Rule," May 14, 2022, https://theicct.org/comments-epa-proposed-hdv-rule-may22/.

56 Eamonn Mulholland et al., "The CO_2 Standards Required by Trucks and Buses for Europe to Meet Its Climate Targets," (ICCT: Washington, D.C., in press).

Ambitious scenario used for the other ZEVTC jurisdictions and were used as they provide more granularity on the uptake of ZEVs for different HDV segments.

Finally, we adopted a simplified approach to modeling the split between BEVs and fuel cell electric vehicles (FCEVs). BEVs are expected to dominate the zero-emission HDV market due to better economic performance—based on lower energy costs—and on their superior technology readiness. FCEVs offer higher driving ranges and more flexibility, though; they are needed in use cases with longer-than-average distance requirements and for trucks operating in remote areas with little availability of charging infrastructure, typically for long-haul trucking. We assumed that the use of a fuel cell electric truck is necessary when a vehicle has a daily mileage requirement above 800 km; such vehicles are less than 3% of all HDVs across ZEVTC jurisdictions, and significantly less in most jurisdictions.

Appendix B. Detailed results for ZEVTC jurisdictions

Number of electric vehicles in 2030

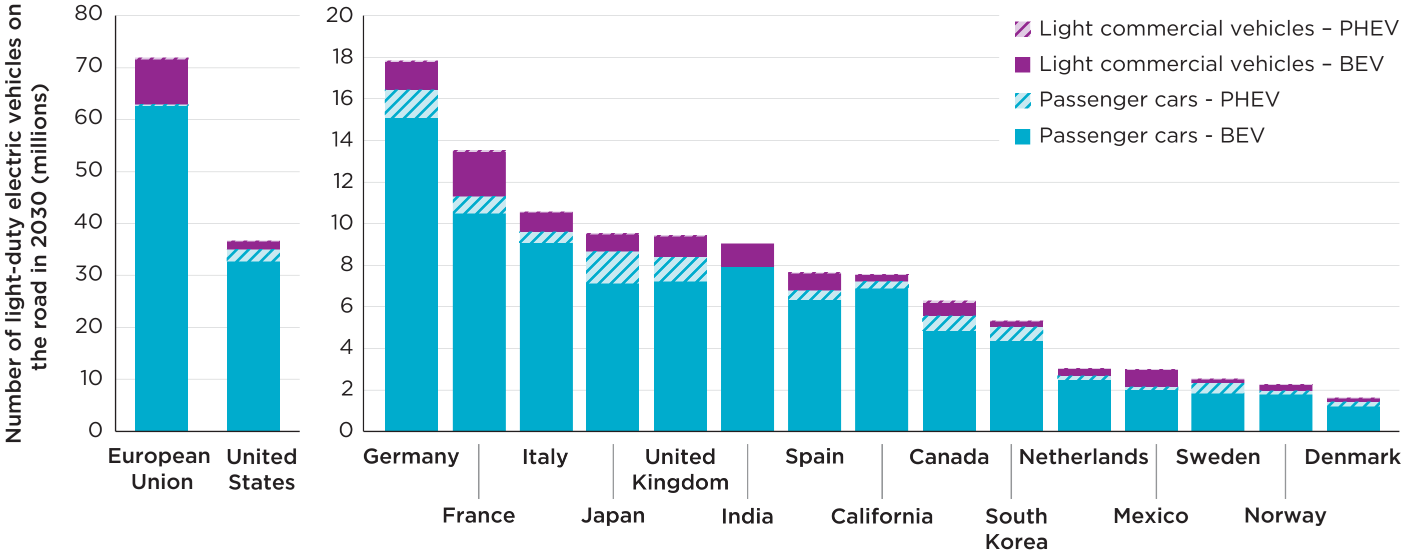

Figure B1. Number of light-duty electric vehicles on the road in ZEVTC jurisdictions in 2030.

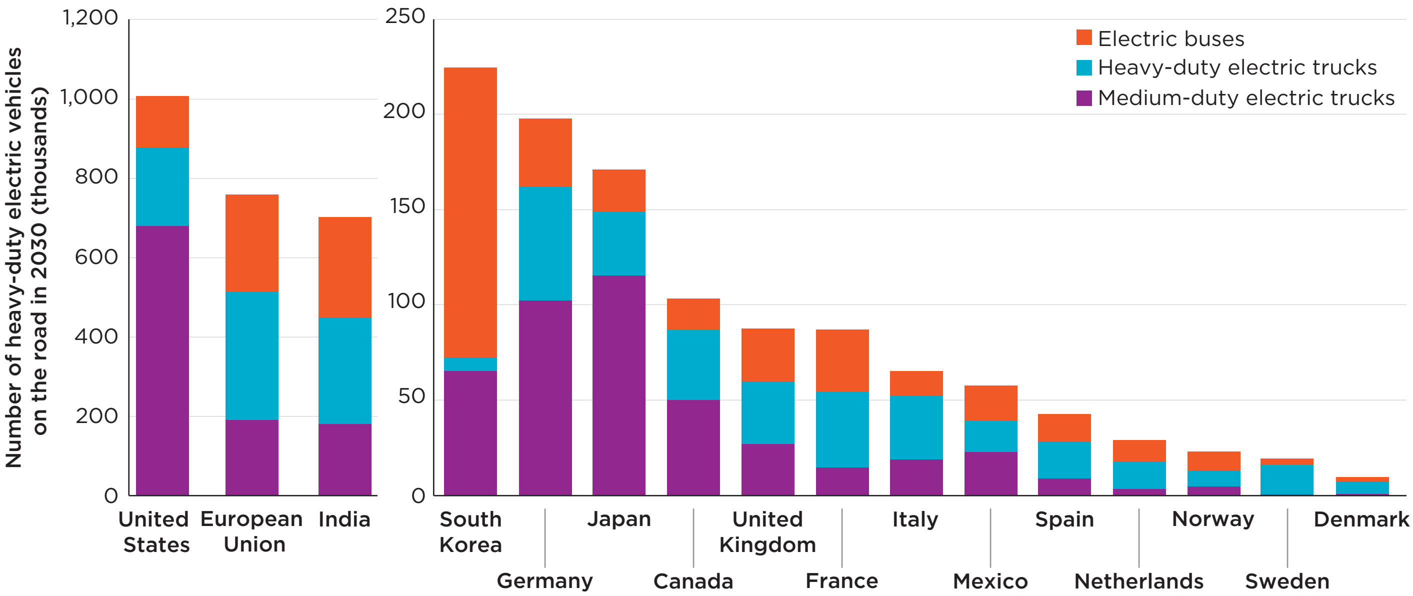

Figure B2. Number of heavy-duty electric vehicles on the road in ZEVTC jurisdictions in 2030.

Public installed power output

Absolute number of chargers is an easy-to-understand metric for public charging infrastructure goals. However, it leaves limited flexibility for the type of chargers to be deployed. Indeed, an 11 kW charger is not equivalent to a 150 kW charger. To consider the variety of public charging infrastructure that can be deployed, governments could set objectives in terms of total installed public capacity under the form of total installed public power output to be deployed in kilowatts per BEV and per PHEV, respectively. This is already under consideration in the European Union, as explained in the policy section.

The total public installed power output needed per BEV and PHEV depends on many factors, the four major ones being electric vehicle penetration, vehicle miles driven, vehicle efficiency, and access to private charging. Figure B1 presents the public accessible power output in kilowatts per BEV (plain lines) and per PHEV (dotted lines) for each jurisdiction as a function of electric vehicle stock share.

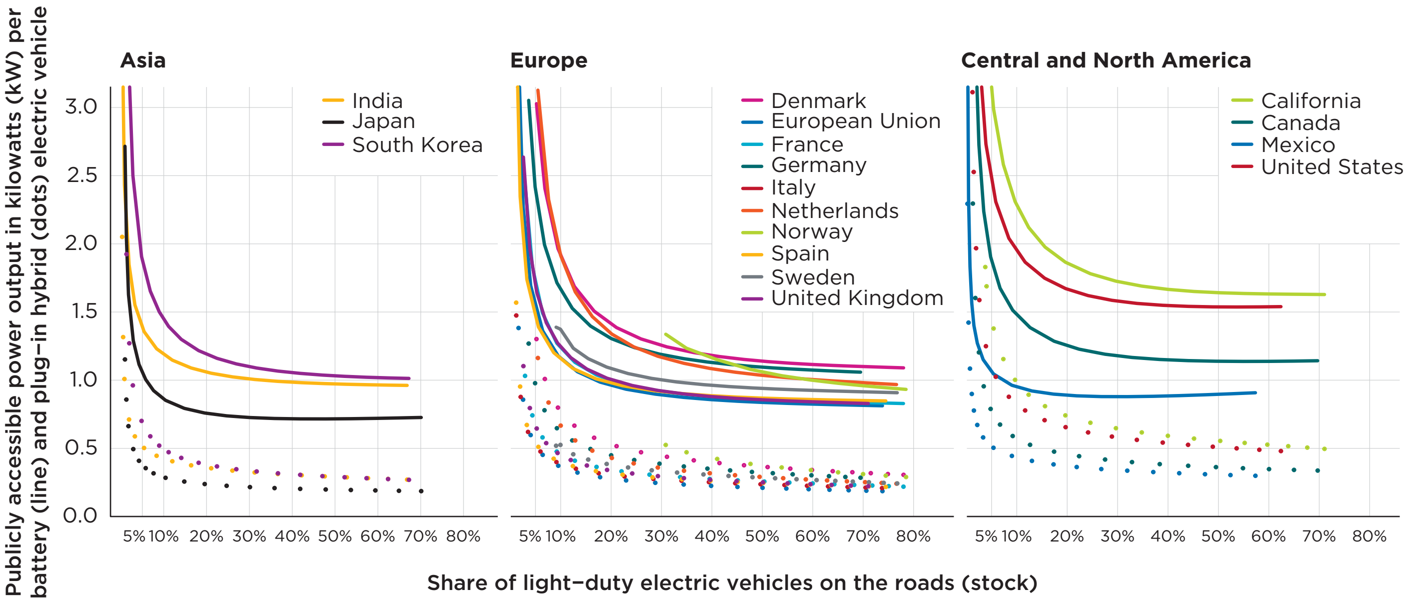

Figure B3. Publicly accessible power output in kW needed per BEV (line) and PHEV (dots) as a function of light-duty electric vehicles stock share.

As shown, power output needs per electric vehicle decrease exponentially as a function of electric vehicle share. With more efficient utilization of deployed charging infrastructure, power output needs per electric vehicle plateau between 0.85 and 1 kW per BEV in most European jurisdictions and in Mexico, India, and South Korea; the plateau is slightly lower for Japan and higher for California, Canada, and the United States. For PHEVs, the needs plateau at 0.6 kW per PHEV for California and the United States, 0.2 for Japan, and between 0.3 and 0.4 for all the other jurisdictions. These plateaus are expected be reached no later than 2030 in all jurisdictions.

The variations by jurisdiction come from different vehicle miles traveled, vehicle efficiency, and access to private charging. While North American drivers have more access to private charging than European and Asian drivers, due to more cars parked off-street, this is largely offset by more vehicle miles traveled and lower electric vehicle efficiency, mostly due to larger and heavier vehicles. Indeed, as an example, while on average cars in South Korea are driven 8,000 miles per year and have an efficiency of 0.29 kWh per mile, these numbers go up to 12,700 miles per year and 0.45 kWh per miles for an average car in the United States.

In addition, the low power output requirements per PHEV are mainly due to the low share of electric kilometers driven. According to a recently published study, only 45%–49% of private car PHEV driving is done on electricity and the share is just 11%–15% for company cars.[57] If PHEVs were to be driven 100% on electricity, their power output needs would surpass those of BEVs due to lower PHEV efficiency compared to BEVs.

Private chargers growth by 2030

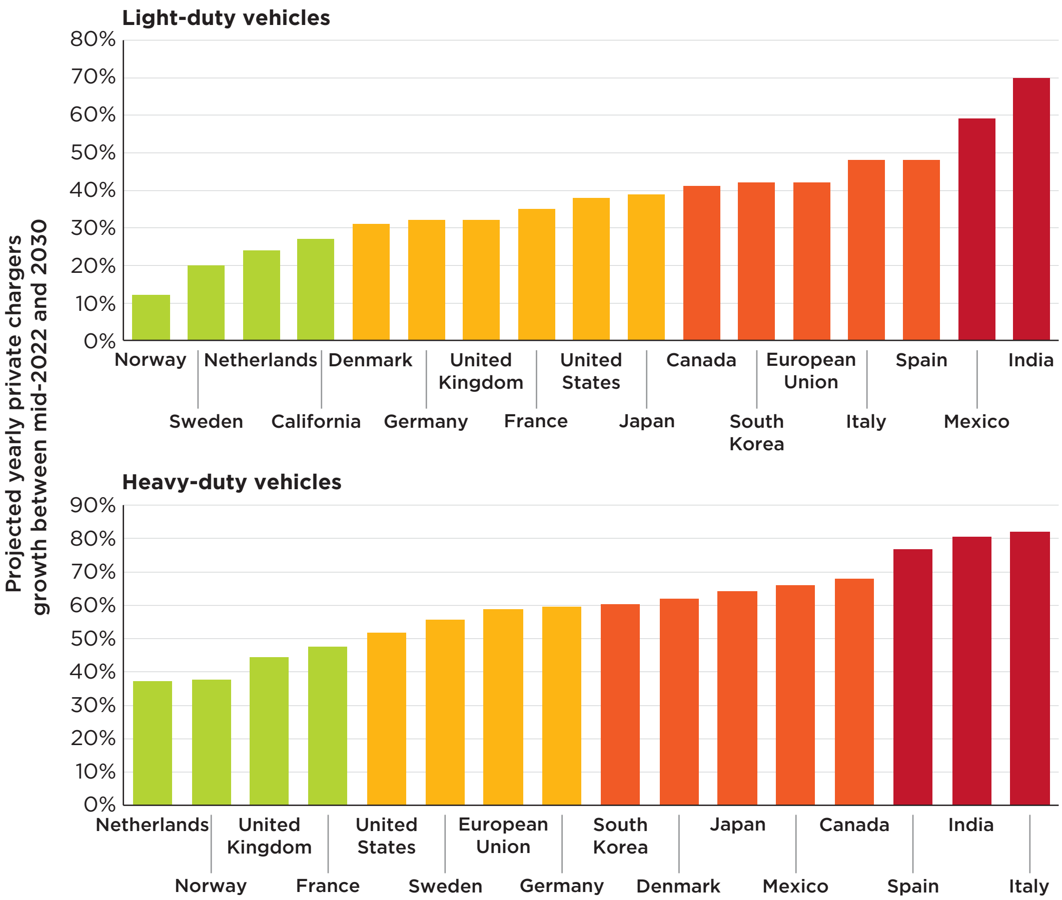

Figure B4. Projected year-to-year private chargers growth for LDVs (top) and HDVs (bottom) between mid-2022 and 2030.

57 Georg Bieker et al. "Real-World Usage of Plug-in Hybrid Vehicles in Europe: A 2022 Update," (ICCT: Washington, D.C., 2022), https://theicct.org/publication/fs-real-world-phev-use-jun22/.

Charging infrastructure and installed power output needs by 2035

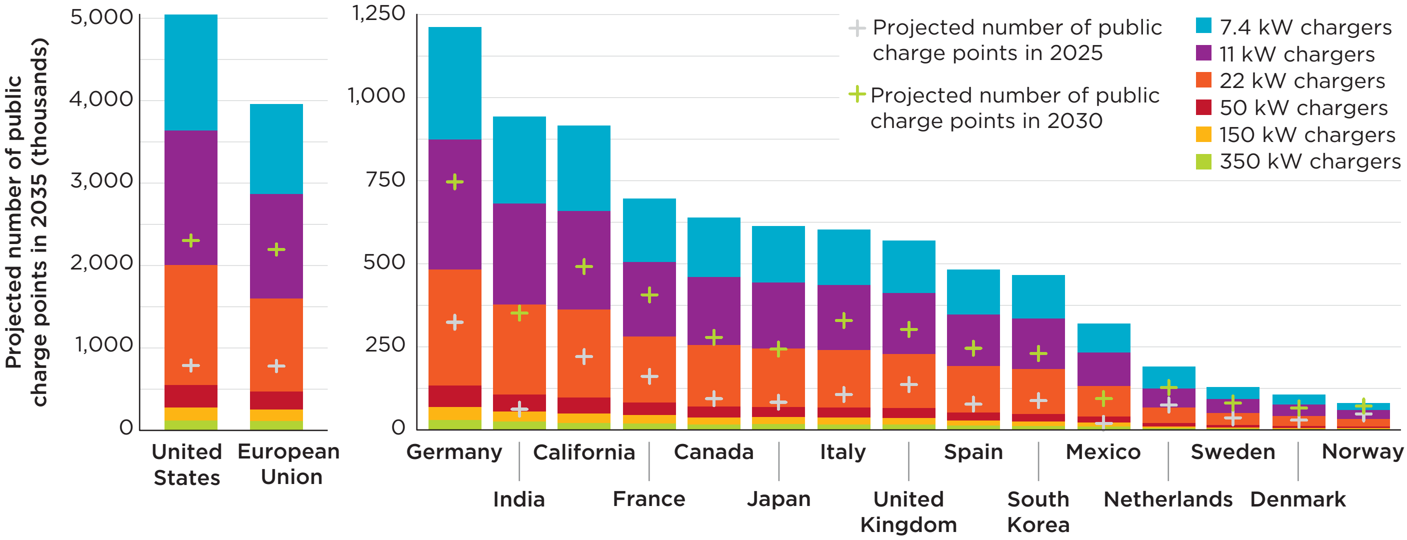

Figure B5. Number of public charge points needed for light-duty electric vehicles in 2025, 2030, and 2035 for each ZEVTC member.

These public chargers will represent an overall installed power output in ZEVTC jurisdictions of 360 GW in 2035, or 1.0 kW per electric vehicle. Note that this does not mean that 360 GW of additional publicly accessible power generation will be needed, as not all chargers will be used simultaneously and at maximum power.

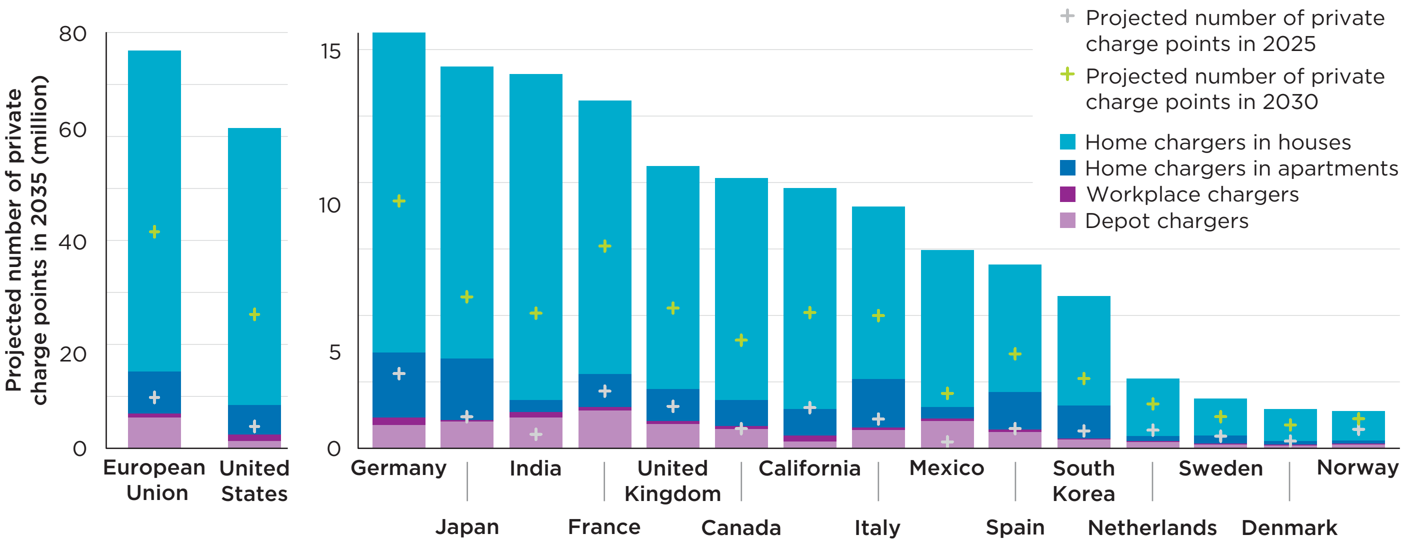

Figure B6. Number of private charge points needed for light-duty electric vehicles in 2025, 2030, and 2035 for each ZEVTC member.

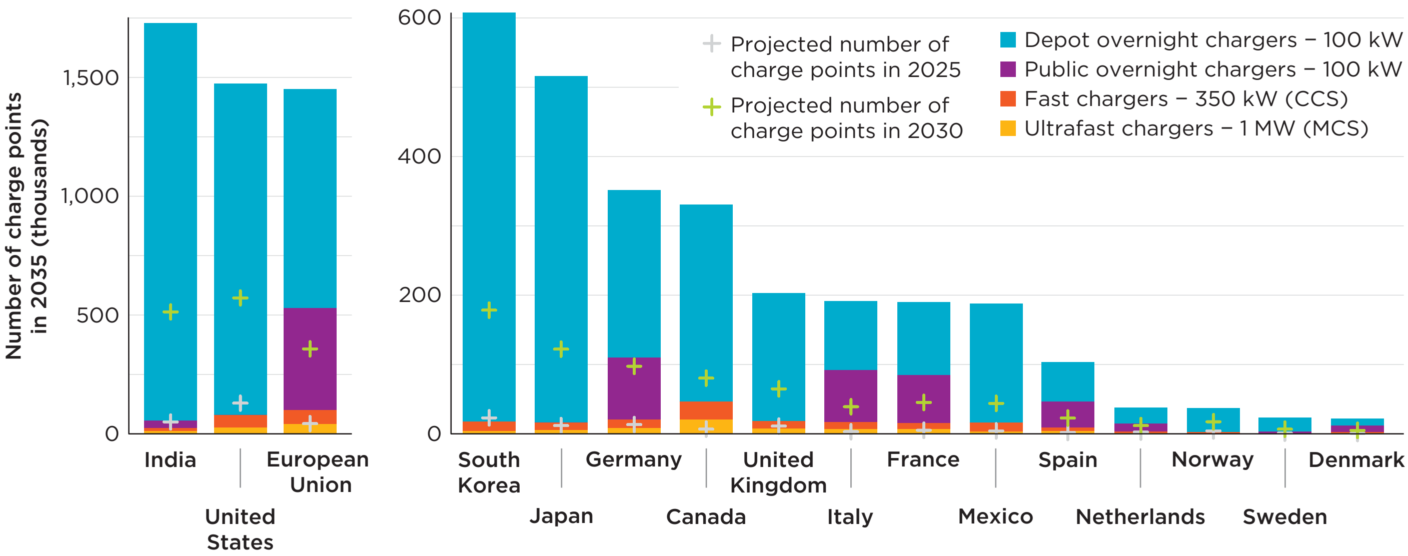

Figure B7. Number of total charge points needed for heavy-duty electric vehicles in 2025, 2030, and 2035 for each ZEVTC member.

Cumulative charging infrastructure cost estimates by 2030 and 2035

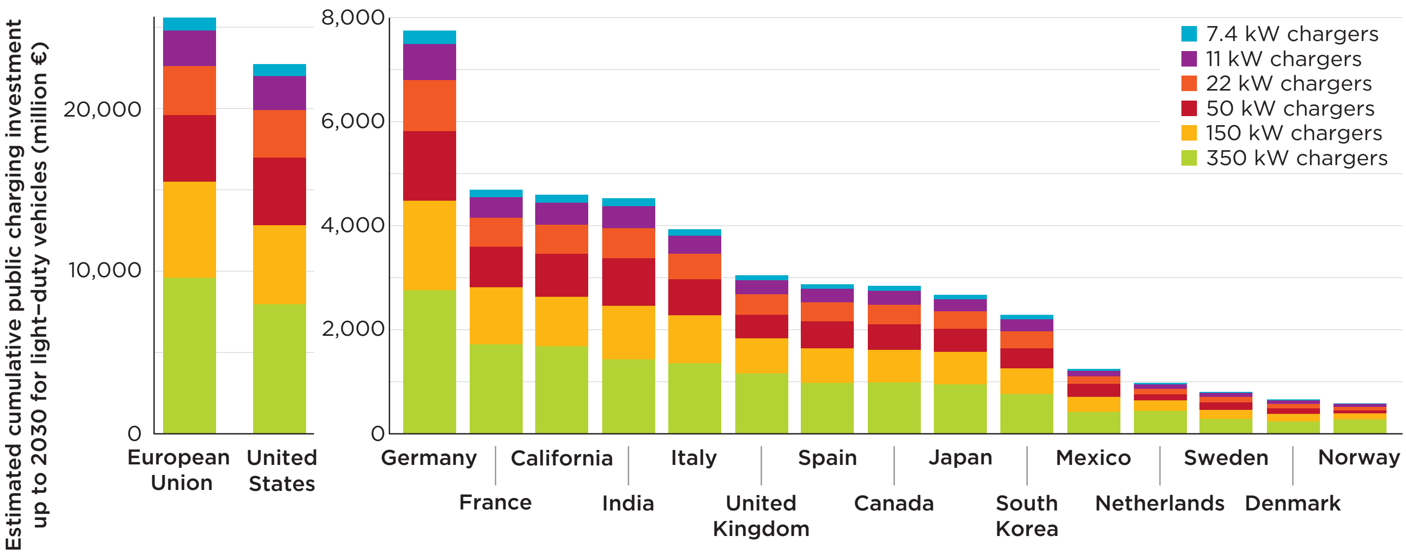

Figure B8. Cumulative public charging infrastructure investment for light-duty vehicles up to 2030 split per charger type. A different scale is used on the y-axis for the European Union and the United States.

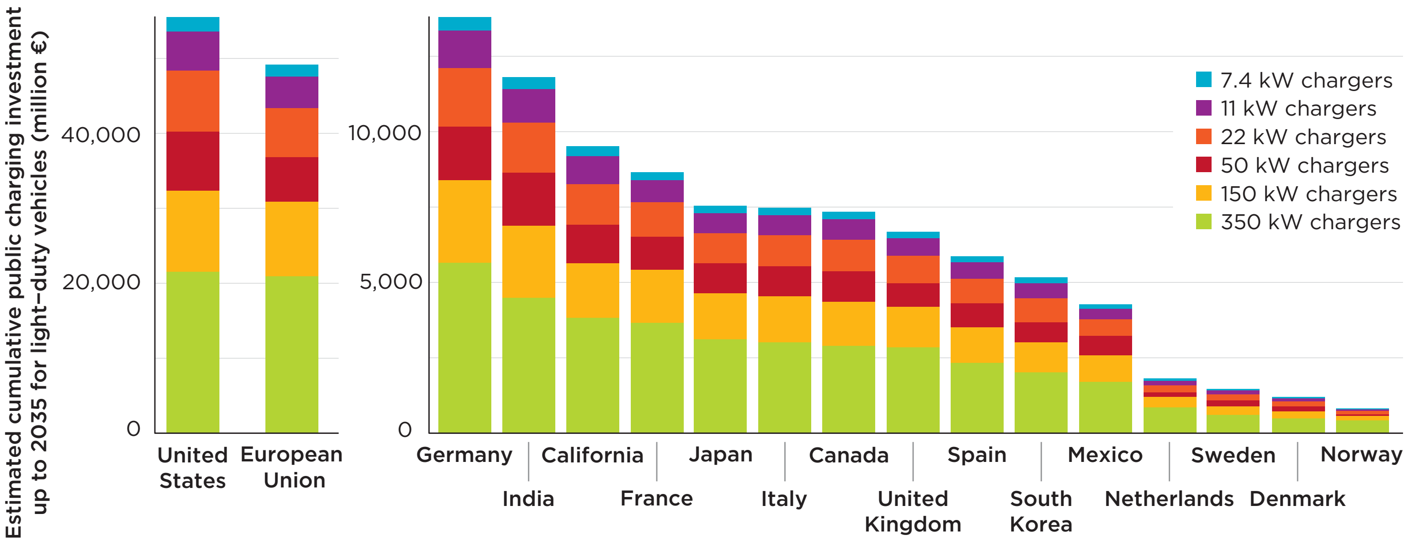

Figure B9. Cumulative public charging infrastructure investment for light-duty vehicles up to 2035 split per charger type. A different scale is used on the y-axis for the European Union and the United States.

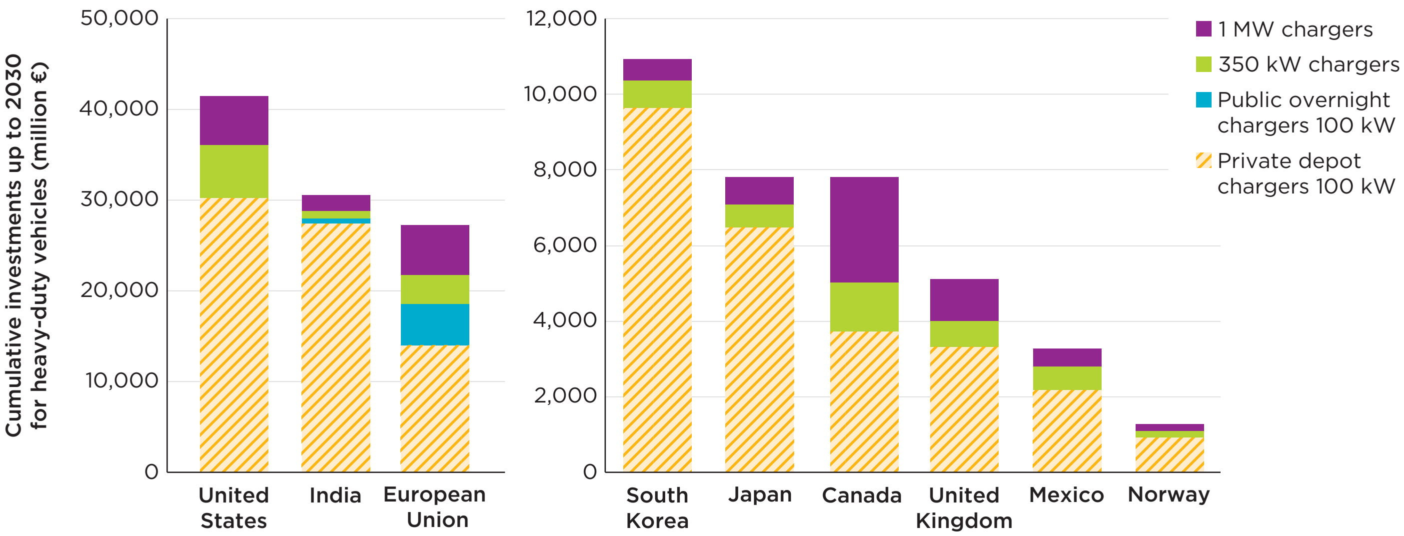

Figure B10. Cumulative charging infrastructure investment for heavy-duty vehicles up to 2030. A different scale is used on the y-axis for the European Union, India, and the United States. Yellow patterns are used for private chargers and full bars for public chargers.

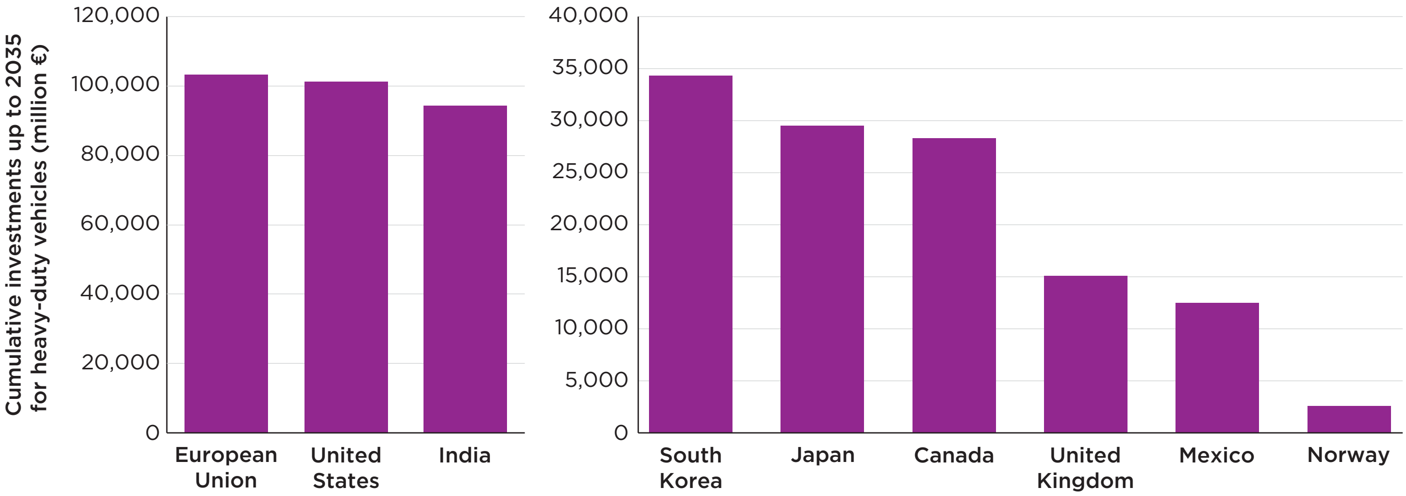

Figure B11. Cumulative charging infrastructure investment for heavy-duty vehicles up to 2035. A different scale is used on the y-axis for the European Union, India, and the United States.

Appendix C. Public and private investment

An overview of national infrastructure plans that include substantial government funding and private sector commitments are presented in this section. Table C1 details investments made by ZEVTC jurisdictions in their charging infrastructure networks.

Table C1. Government funding for charging and refueling network, 2021–2022

Country	Policy name	Date of announcement	Committed funding
Germany	Directive on the Promotion of Light and Heavy Commercial Vehicles	August 2021	€5 billion to fund charging and refueling stations for commercial cars and trucks by 2024
France	ADVENIR	December 2021 (update)	€320 million to finance 100,000 public chargers by 2025
United Kingdom	Electric Vehicle Infrastructure Strategy	March 2022	£1.6 billion to accelerate the rollout of charging infrastructure.
United States	Infrastructure Investment and Jobs Act	November 2021	$7.5 billion to support the installation of 500,000 chargers by 2030
	Inflation Reduction Act	August 2022	$1.7 billion in tax credits for installing charging and refueling stations until 2031
Canada	2030 Emissions Reduction Plan	March 2022	C$991 million to install 50,000 new chargers
Japan	Green Growth Strategy	June 2021	¥6 billion to install 150,000 charging and 1,000 hydrogen stations by 2030

Investing early, prior to demand, will build market confidence before the charging network reaches profitability. For instance, installing fast charging stations along major highways will improve confidence in ZEVs for longer journeys. In March 2022, the U.K. government committed £1.6 billion to fund a nationwide network of 300,000 public chargers by 2030, a tenfold increase from 2021.[58] The fund aims to attract private capital to install high-powered chargers at motorway service areas by the end of 2023. The U.S. Infrastructure Investment and Jobs Act, passed in November 2021, provides $7.5 billion in dedicated investment.[59] The first round of funding from the aforementioned NEVI Formula Program will prioritize the installation of high-power charging on highways.[60] As of June 2022, the program catalyzed $700 million in private sector commitments, including for installation of ultra-fast chargers.[61]

In jurisdictions with strong policy support, car and truck manufacturers have committed to installing public charging in underserved areas and to supporting early-stage charging technologies. GM plans to invest $750 million to install 40,000 public

58 The U.K. Government, "Taking Charge: The Electric Vehicle Infrastructure Strategy," March 25, 2022, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1065576/taking-charge-the-electric-vehicle-infrastructure-strategy.pdf.

59 Infrastructure Investment and Jobs Act, Pub. L. No. 117–58, 117th Cong. (2021), https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

60 The U.S. Department of Transportation, Federal Highway Administration, "President Biden, USDOT and USDOE Announce $5 Billion over Five Years for National EV Charging Network, Made Possible by Bipartisan Infrastructure Law," news release, February 10, 2022, https://highways.dot.gov/newsroom/president-biden-usdot-and-usdoe-announce-5-billion-over-five-years-national-ev-charging.

61 The White House, "Fact Sheet: Biden-Harris Administration Catalyzes More than $700 Million in Private Sector Commitments to Make EV Charging More Affordable and Accessible," news release, June 28, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/28/fact-sheet-biden-harris-administration-catalyzes-more-than-700-million-in-private-sector-commitments-to-make-ev-charging-more-affordable-and-accessible/.

chargers in underserved rural and urban areas across the United States and Canada by 2025.[62] In July 2021, Daimler Trucks, Volvo, and Traton Group announced a joint venture (JV) that will allocate €500 million to establish a public charging network for battery electric heavy-duty long-haul trucks in Europe.[63]

Though many governments and private-sector actors have committed funding to charging infrastructure, a bigger financial push is needed to fund infrastructure costs through the ZEV transition. Polluter-pay vehicle emission policies that impose tax on polluting vehicles and incentivize the adoption of ZEVs could lower government expenses.[64] Other funding sources include utility ratepayer revenue, fuel duties, low-carbon fuel standards, and fines for violations of clean air rules. In addition to government funds, emerging markets are partnering with private companies and bringing in international funding to support infrastructure development.[65] As the ZEV market reaches an inflection point, redirecting funding from purchase subsidies to charging infrastructure could accelerate ZEV deployment.

62 General Motors, "GM to Expand Access to EV Charging with More than 40,000 Community-Based Charging Stations and New Smart EV Supply Equipment," news release, October 26, 2021, https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2021/oct/1026-ultium-charger.html.

63 Mercedes-Benz Group, "Daimler Truck, the Traton Group and Volvo Group Plan to Pioneer a European High-Performance Charging Network for Heavy-Duty Trucks," news release, July 5, 2021, https://group.mercedes-benz.com/investors/reports-news/financial-news/20210705-high-performance-charging-network.html.

64 Slowik et al., "Funding the Transition to All Zero-Emission Vehicles."

65 Tanzila Khan et al., "A Critical Review of ZEV Deployment in Emerging Markets," (ICCT: Washington, D.C., 2022), https://theicct.org/wp-content/uploads/2022/02/ZEV-EMDE-white-paper-A4-v3.pdf.

Appendix D. Glossary of definitions for this paper

Vehicle

Heavy-duty vehicle: Includes buses, medium- and heavy-duty vehicles, meaning all road vehicles above 3.5 tons.

Light-duty vehicle: Includes passenger cars and light commercial vehicles. two- and three-wheelers are excluded.

Charging infrastructure

Charging infrastructure: Encompasses wired stationary charging only and does not consider other emerging charging solutions such as battery swapping and overhead catenary charging.

Wired stationary charging: This is the most common method of charging for electric vehicles as of 2022. The charger gets wired straight into the grid or any power source on one side and plugs into the vehicle on the other side through a cable that allows electricity to flow from the grid to the vehicle.

Charging infrastructure cost: Includes chargers' hardware, software, installation, and planning. Grid upgrade costs are not included due to too much uncertainty and variation based on local conditions.

Charging point/charger: Device through which electricity is transferred from the grid to the electric vehicle. There are two main categories of public chargers: normal and fast/ultra-fast.

Public charger: Charger accessible to the general public, with some potential restrictions on accessibility to specific customers. Public chargers encompass normal, fast urban, and fast along major roads chargers.

Private charger: Charger only accessible to one or few specific vehicles. This category encompasses home chargers in houses and apartments, workplace chargers, and depot chargers.

Depot charger: Private charger dedicated to a specific vehicle fleet, mostly used at night to recharge light and heavy commercial vehicles.

Normal charger: Charger with power output below 22 kW, most of the time delivering alternative current (AC).

Fast charger: Charger with power output above 22 kW (most of the time above 50kW), delivering direct current (DC).

The main difference between AC (normal) and DC (fast) charging is where the conversion from AC to DC happens. Only DC current can be fed into the battery of an electric vehicle. Therefore, when AC chargers are used, the AC current is converted to DC current by the electric vehicle's on-board converter. For DC chargers, the current is converted in the charger itself. Because there is more space in the charger than in the vehicle, larger converters can be used in chargers. This is why DC charging is faster (higher power output in kW) than AC charging.

Energy and power

Electricity/energy fed in an electric vehicle: It is in kilowatt-hour (kWh) and is equivalent to the gasoline fed in a combustion engine.

Power: Amount of energy transferred per unit of time. It is usually expressed in kilowatt ($kW = 10^3$ W).

Power generation: Amount of power used simultaneously.

Power output of a charger: Power delivered to an electric vehicle through a charger. It is always inferior to the rated power output of the charger. It is usually expressed in kilowatt (kW). The higher the power output, the faster the electric vehicle is recharged.

Rated power output of a charger: Maximum power that a charger can deliver to a connected vehicle. It is usually expressed in kilowatt (kW) and also called charger's speed.

Installed power output of chargers: Sum of all the rated power output of installed chargers. It is usually expressed in gigawatts ($GW = 10^6$ kW).

Installed power capacity of an installation/country: Maximum possible electricity generation that can be produced by a certain installation/country and is usually given in gigawatts (GW) or megawatts ($MW = 10^3$ kW).