Grid Integration of Electric Vehicles

A manual for policy makers

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Abstract

This policy makers manual is prepared under the framework of the Global Environment Facility programme aimed at supporting low- and middle-income economies in their transition to electric mobility. It aims to serve as a guide for policy makers to effectively integrate electric vehicle charging into the grid, thereby supporting road transport electrification and decarbonisation. The key steps can be summarised as preparing institutions for the shift to electric mobility, assessing the impacts on the grid, deploying measures for grid integration and improving power system planning. Each of these steps is informed by insights from various studies and inputs from international stakeholders, with recommendations based on best practices from around the world.

Acknowledgements, contributors and credits

Luis Lopez is the lead author of this manual under the guidance of Jacques Warichet and Cesar Alejandro Hernandez Alva, former Head of the Renewable Integration and Secure Electricity Unit. IEA colleagues Juha Köykkä and Julia Guyon also contributed to the analysis. Alejandra Bernal, Joerg Husar, Rebecca McKimm and Zhiyu Yang from the IEA Global Energy Relations Office, former IEA colleagues Woan Ho Park and Daniela Quiroga Vergara, and IEA-Latin America consultant Luiz de Oliveira also contributed to this report.

Keisuke Sadamori, Director of the Energy Markets and Security Directorate, provided valuable feedback. Valuable comments and feedback were also provided by Pauline Henriot, Zoe Hungerford, Aditya Ramji, Cornelia Schenk, Jacob Teter and Per-Anders Widell.

Adam Majoe edited this report. Thanks go to the Communications and Digital Office – especially to Jad Mouawad, Head of the Communications and Digital Office, Astrid Dumond and Therese Walsh – for their help with production and for providing website materials. Anna Kalista also provided essential support.

An online webinar on managing the grid integration of electric vehicles was held on 15 March 2022. The speakers and participants provided valuable inputs for this report.

This report benefited greatly from comments and feedback from many external experts, including:

Doris Agbevivi (Energy Commission Ghana), Arina Anisie (IRENA), Molly Blatchly-Lewis (WBCSD), Victor Bonilla (EBRD), Karima Boukir (Enedis), Jaap Burger (Regulatory Assistance Project), Francisco Cabeza (Element), Francois Cuenot (UNECE), Shyamasis Das (Independent Consultant), Thomas Deloison (WBCSD), Michael Drtil (Hitachi Energy), Aaron Fishbone (Green Way), Nikos Hatziargyriou (National Technical University of Athens), Harini Hewa Dewage (4R Digital), Nishi Hidetaka (METI), Julia Hildermeier (RAP), Antonio Iliceto (ENTSO-E/Terna), Chaitanya Kanuri (WRI), Tarek Keskes (ESMAP World Bank), Yanchao Li (World Bank), Mattia Marinelli (DTU), Indradip Mitra (GIZ), Sajid Mubashir (Bureau of Indian Standards), Hiten Parmar (uYilo eMobility Programme), Luis Felipe Quirama (UNEP), Chris Rimmer (Cenex), Sacha Scheffer (Rijkswaterstaat), Sudhendu Jyoti Sinha (NITI Aayog), Urska Skrt (WBCSD), Chris Vertgewall (RWTH Aachen), Lulu Xue (WRI) and Zifei Yang (ICCT).

The report was prepared by the International Energy Agency under the Global E-Mobility Programme funded by the Global Environment Facility. The work could not have been achieved without the financial support provided by the Global Environment Facility and inputs from many of the partners and experts highlighted above. In particular, we would like to acknowledge the United Nations Environment Programme as the lead implementing agency under the programme and all their efforts in co-ordinating the preparations, planning and roll-out of its activities.

Comments and questions on this report are welcome and should be addressed to: gef.emobility.wg4@iea.org

Executive summary

The electrification of road transport is a major driver of decarbonisation in the IEA's Net Zero Emissions by 2050 Scenario, and providing charging solutions will be crucial for supporting this transition. The power sector plays a key role in ensuring a secure supply of electricity for electric vehicle (EV) charging, and in taking advantage of EV flexibility through seamless integration with the power system.

This manual is intended to support policy makers in assessing and mitigating the impacts of electric mobility on the power sector and designing strategies to leverage the flexibility of EVs. It provides key recommendations in four main areas: the readiness of institutions, impact assessment of EV charging, design of operational measures to integrate EVs as an energy resource, and power system planning.

Summary of policy recommendations to integrate EV charging into the grid

① Prepare institutions for the electric mobility transition

1. Engage electric mobility stakeholders
2. Break silos in planning and policy making

② Assess the power system impacts

1. Define an electric mobility strategy
2. Gather data and develop insights
3. Assess the grid impacts under mobility scenarios

③ Deploy measures for grid integration

1. Accommodate all charging solutions but encourage managed charging
2. Facilitate aggregation by enforcing standards and interoperability
3. Value the flexibility of EVs
4. Co-ordinate EV charging with renewables
5. Incentivise smart-readiness

④ Improve planning practices

1. Conduct proactive grid planning
2. Reflect the full value of EV charging

Preparing institutions for the shift to electric mobility

While electric mobility is accelerating in many locations around the world, preparing institutions can help ensure that the shift to electric mobility happens efficiently by taking advantage of various synergies. Electric mobility is cross-sectoral and requires institutions to engage with a wide variety of stakeholders from the mobility and power sectors as well as the building and real estate sectors. To engage efficiently across sectors and support planning, silos in ministries as well as in the industry need to be broken down.

Policy makers can start preparing institutions by **engaging electric mobility stakeholders** by creating multidisciplinary working groups. Working groups serve as focal points where stakeholders can learn about the concerns and motivations of others, and where common frameworks can be developed to help push electric mobility forward.

Policy makers can **break silos** by establishing co-operation at the policy-making level and designating contact persons to be in charge of cross-sectoral co-ordination so they can maximise synergies.

Assessing the impacts of electric mobility on the power sector

Like any other electric load, EVs will impact the power system based on their power and energy requirements and on the grids from which they are charging. Depending on the degree of uptake, line or transformer loading or power quality problems may not be encountered when EVs charge simultaneously or fast charge in commercial or industrial areas but may be encountered in residential areas. Moreover, even with sufficient network capacity, the coincidence of EV charging with peak electricity consumption will increase marginal generation requirements and result in additional system costs.

The vehicle segments electrified and their corresponding charging solutions, along with user preferences and local mobility patterns, determine how and where these impacts take place. Regular commuters with personal EVs mainly recharge in the evening at home or during the day at work if the charging infrastructure is available. Meanwhile, e-buses and e-trucks require high charging power for overnight charging at depots and even higher power for mid-travel stops. Hence, it is important for policy makers to **develop an electric mobility strategy** to consider all of these factors and determine the vehicle electrification priorities and the charging solutions that accompany them.

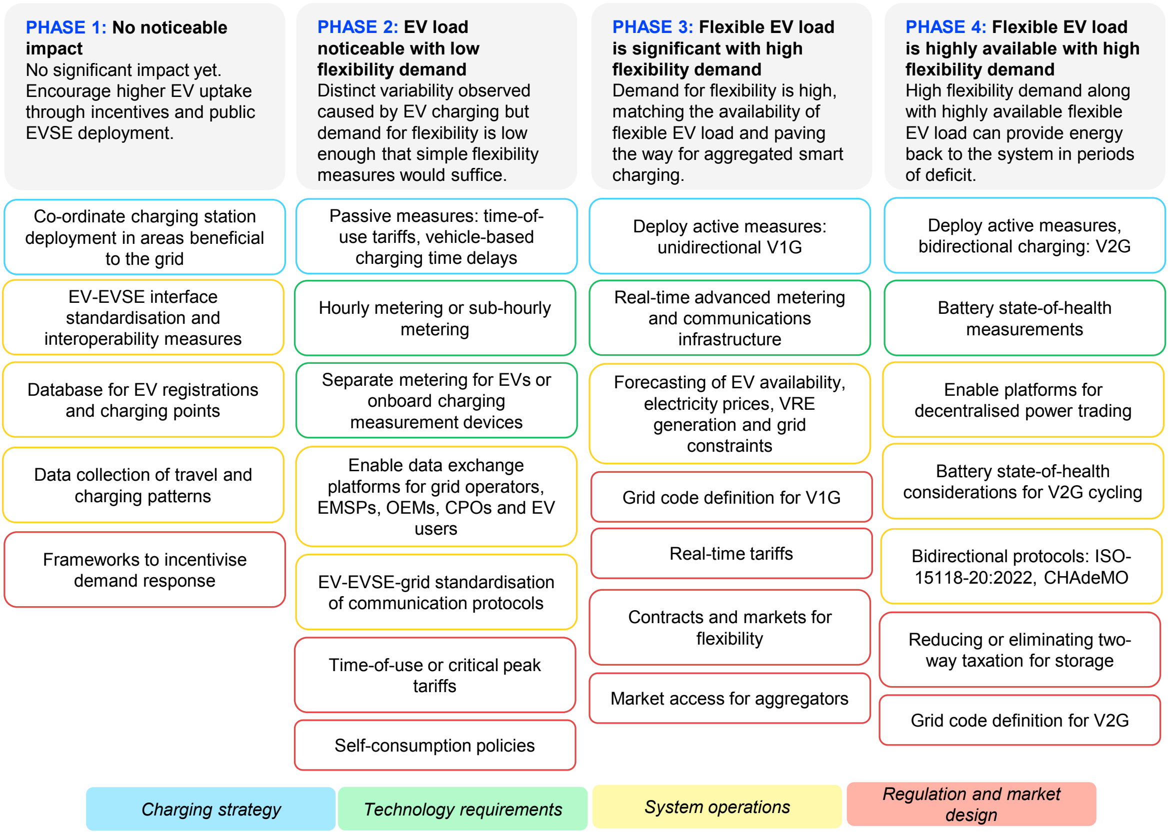
Obtaining data on travel needs and charging patterns through travel surveys, global positioning system (GPS) technologies and charging databases can provide insights for policy makers and aid in modelling EV uptake and charging profiles. To account for forecasting uncertainties, policy makers can use **mobility scenarios when assessing the impacts on the grid** to ensure that decisions on grid investments can adapt to possible changes in the landscape.

Due to variations in local mobility and power system contexts, dedicated studies are necessary to adequately assess the grid impacts and deploy comprehensive plans. In this respect, an upcoming interactive tool on EV charging under the Global Environment Facility's electric mobility programme, along with this policy manual, aims to support policy makers in these endeavours.

Deploying measures for the grid integration of EVs

While electric mobility can have significant impacts on the grid, several measures exist to mitigate the impacts and turn them instead into opportunities for flexibility. This manual provides a simple framework for EV grid integration to help policy makers prioritise charging strategies according to the conditions of their EV uptake and power system needs. The framework is structured around four phases corresponding to increasing volumes of flexible EV load and increasing system demand for flexibility.

Framework for grid integration of electric vehicles



PHASE 1: No noticeable impact No significant impact yet. Encourage higher EV uptake through incentives and public EVSE deployment.	**PHASE 2: EV load noticeable with low flexibility demand** Distinct variability observed caused by EV charging but demand for flexibility is low enough that simple flexibility measures would suffice.	**PHASE 3: Flexible EV load is significant with high flexibility demand** Demand for flexibility is high, matching the availability of flexible EV load and paving the way for aggregated smart charging.	**PHASE 4: Flexible EV load is highly available with high flexibility demand** High flexibility demand along with highly available flexible EV load can provide energy back to the system in periods of deficit.
🟦 Co-ordinate charging station deployment in areas beneficial to the grid	🟦 Passive measures: time-of-use tariffs, vehicle-based charging time delays	🟦 Deploy active measures: unidirectional V1G	🟦 Deploy active measures, bidirectional charging: V2G
🟨 EV-EVSE interface standardisation and interoperability measures	🟩 Hourly metering or sub-hourly metering	🟩 Real-time advanced metering and communications infrastructure	🟩 Battery state-of-health measurements
🟨 Database for EV registrations and charging points	🟩 Separate metering for EVs or onboard charging measurement devices	🟨 Forecasting of EV availability, electricity prices, VRE generation and grid constraints	🟨 Enable platforms for decentralised power trading
🟨 Data collection of travel and charging patterns	🟨 Enable data exchange platforms for grid operators, EMSPs, OEMs, CPOs and EV users	🟥 Grid code definition for V1G	🟨 Battery state-of-health considerations for V2G cycling
🟥 Frameworks to incentivise demand response	🟨 EV-EVSE-grid standardisation of communication protocols	🟥 Real-time tariffs	🟨 Bidirectional protocols: ISO-15118-20:2022, CHAdeMO
	🟥 Time-of-use or critical peak tariffs	🟥 Contracts and markets for flexibility	🟥 Reducing or eliminating two-way taxation for storage
	🟥 Self-consumption policies	🟥 Market access for aggregators	🟥 Grid code definition for V2G

🟦 *Charging strategy* 🟩 *Technology requirements* 🟨 *System operations* 🟥 *Regulation and market design*

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The main strategy is to maximise the amount of managed charging, as opposed to unmanaged charging. Cost-effective charging solutions that help accelerate the shift to electric mobility should be accommodated by the grid, but opportunities to maximise the share of managed charging should be pursued when possible.

Measures to mitigate **unmanaged charging and encourage managed charging** include providing locational signals, making connections non-firm at certain power levels or at certain times of the day, requiring storage or storage fees, and making the connection fee dependent on power demand or the controllability of the connected EV charger.

In order to unlock the technology and business models necessary to provide flexibility through managed charging, the **flexibility needs to be valued and remunerated**. Policy makers can use tools such as tariff design, contracts and markets for flexibilities, and participation in wholesale markets to reward managed charging.

Individual EVs may be too small to participate in most power markets, but this can be resolved through **standardisation and interoperability measures, thereby aggregating** sufficient numbers of vehicles.

Electric mobility is also an unprecedented opportunity to grow the share of variable renewables in the power system. **EV charging can be co-ordinated with variable renewable energy** generation through incentives and measures to allow the contracting of renewables capacities.

Finally, with all of the potential benefits of managed charging, policy makers should **incentivise the smart-readiness** of ecosystems through minimum communication and control requirements.

Improving power system planning

The rate of electrification of transport and other loads, and the potential cost savings they provide, calls for a fundamental improvement in planning practices to ensure the power system is ready to accommodate and take advantage of them as distributed energy resources.

Co-ordinated and integrated planning practices are becoming essential. These ensure that power sector plans are well co-ordinated within the power sector and with other sectors. In particular, **grid planning needs to be proactive** and anticipate various needs for expansion rather than respond to new requests for connection. Mandated time windows of interconnection and the publication of hosting capacity maps can help streamline interconnection processes. Meanwhile, capacity building to develop modelling capabilities and regulatory incentives tied to supporting electric mobility can help grid operators proactively plan for EV charging demand.

Finally, the scenarios and plans for the power sector need to properly **reflect the full value of EV charging**. Revisiting regulatory design to reduce bias on capacity expenditure helps grid operators put more focus on leveraging available flexibility and reducing costs for everyone. Likewise, revisiting criteria for grid expansion and system planning can help ensure that the cost savings from EV charging flexibility are recognised and accounted for when developing grids.

Introduction

Context

The electrification of road transport is a key pillar of the IEA's Net Zero Emissions by 2050 Scenario for reducing transport emissions. Emissions could be reduced by around 94% if electric mobility were ramped up from 11 million vehicles today to 2 billion in 2050.[1] By eliminating tailpipe emissions, EVs would also improve local air quality and result in health improvements for cities and communities.

Electric mobility can also be a tool for energy security. By 2030, the global uptake of EVs could displace oil demand from 2 million barrels per day in the IEA's Stated Policies Scenario to about 4.6 million barrels per day in the IEA's Announced Pledges Scenario.[2] For many countries that are highly dependent on oil imports, electrifying transport could allow them to diversify and use domestic primary energy resources, such as hydro, solar and wind. The energy demand on the power systems would be significant but would only constitute a minor share of the countries' electricity consumption. According to the Stated Policies Scenario, approximately 709 TWh of final electricity demand globally would be needed in 2030, equivalent to the total power generation of Canada and the Netherlands in 2019, but on average would only constitute 2.7% of individual countries' total electricity generated.

On the other hand, local constraints on grid capacity are expected to be the main challenge due to the high power levels associated with the simultaneous charging of EVs. For example, in the Netherlands, about 3 000 neighbourhoods with at least 100 EVs are expected to exceed network capacity by 2025 due to faster-than-expected growth in EV uptake. In California, a local distribution system would need to upgrade five times more feeders than originally planned to accommodate EVs by 2030. Moreover, the concurrent electrification of heating and acquisition of air conditioning and distributed PV could pose challenges to network capacities, in some cases exacerbating or exceeding the impact of EVs.

Despite these challenges, electric mobility offers opportunities for flexibility due to its storage capabilities. Total battery capacity from EVs could be as high as 29 TWh by 2030 and 186 TWh by 2050 in the Net Zero Emissions by 2050 Scenario, providing a high potential for flexibility while the EVs are charging. Taking advantage

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[1] A comparison of the life cycle emissions of EVs and internal combustion engine vehicles is relevant for policy discussions, especially when considering battery extraction, manufacturing and recycling. However, this is not within the scope of this report. For more details, see the International Council on Clean Transportation's (ICCT) report on the life cycle emissions of combustion engines and electric passenger cars.

[2] The Announced Pledges Scenario is based on the different countries' announcements of their 2030 targets and longer-term net zero pledges, regardless of whether they are anchored in legislation or in updated nationally determined contributions.

of this opportunity would require investments in communications and digital infrastructure as well as changes in market design and regulation.

Policy makers hence need to ensure that their power systems are ready, and the preparation must be done immediately and proactively. Electric mobility is already becoming mainstream, representing 5%, 16% and 17% of total light-duty vehicle sales in 2021 in the United States, the People's Republic of China (hereafter, 'China') and Europe and up to 30% of LDV sales in the Netherlands. It is also taking hold in emerging economies, such as India, where electric three-wheelers constituted 46% of total sales between April 2021 and March 2022.

One key aspect of policy intervention relates to EV charging. While adapting EV charging to the demands of EV users can help accelerate the uptake of electric mobility, shaping its deployment to minimise impacts on the grid can reduce costs and contribute to sustainability goals. Co-ordinating the planning and deployment of charging infrastructure with the planning of the power system grids can help ensure the timely delivery of charging solutions to support the shift to electric mobility.

Purpose

Given the increasing role of electric mobility in many countries, the IEA, as one of the implementing agencies of the Global Environment Facility-funded Global Programme to Support Countries with the Shift to Electric Mobility, has produced this manual for policy makers to help facilitate the grid integration of EV charging and renewables and outline important considerations for a secure, clean and affordable energy system. It is also a deliverable under the Clean Energy Ministerial's Electric Vehicles Initiative.

This manual is primarily targeted at policy makers in the power sector, highlighting the key intersections with other stakeholders, especially those in the transport and building sectors. It aims to serve as a guide for policy makers on how to prepare for the shift to electric mobility and effectively take advantage of the opportunities from EVs.

The manual organises the technical and policy insights from grid integration practices around the world and is arranged in four chapters corresponding to the key steps recommended to policy makers:

- Step/Chapter 1 is about preparing institutions for the shift towards electric mobility. It introduces the key stakeholders who need to be rallied to support this shift and the need to break silos between sectors, in particular between mobility, the power sector and buildings/real estate.
- Step/Chapter 2 is about understanding and assessing the grid impacts of electric mobility. It introduces the dynamics of EV charging and explains how vehicle electrification patterns and local conditions affect the power system. It highlights the need to develop robust scenarios for grid planning and operations.

- Step/Chapter 3 is about deploying measures for grid integration. It explains the policies, standards and regulations that aim to reduce the impact of EV charging and even turn them into an opportunity for the power system, helping balance the system and integrate more renewables.
- Step/Chapter 4 is about improved planning practices. It explains how proactive grid planning can help accommodate future charging needs, and the need to reflect the full value of EV charging flexibility in planning.

1. Prepare institutions for the electric mobility transition

Authorities can play a significant role in the shift to electric mobility through policies that enable and accelerate the uptake of electric vehicles (EVs). Therefore, the shift to electric mobility starts from the institutions.

1.1 Engage electric mobility stakeholders

The electric mobility ecosystem involves a wide range of stakeholders, some of which may have had limited interactions among themselves until recently. Given the imperative of maintaining the power system's supply-demand balance at all times, providing charging solutions for EVs entails a high degree of co-ordination among stakeholders. To do so, understanding their concerns and motivations is important.

From the perspective of the power system, stakeholders can be classified into operational stakeholders – those directly involved in the charging operations – and planning stakeholders – those involved in planning and enabling the conditions for vehicle-grid integration to happen.

The engagement of operational stakeholders focuses on accelerating EV uptake by addressing prospective users' range anxiety.[3] Original equipment manufacturers (OEMs) provide portable chargers and charging point operators (CPOs) install public charging infrastructure in collaboration with network operators and retailers to ensure that energy can be sufficiently supplied. Charging programmes may exist, provided by electric mobility service providers (EMSPs) to help reduce costs for EV users by co-operating with aggregators or network operators.

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[3] Range anxiety is the driver's concern that there will not be enough battery storage in the EV to cover the distance required to reach the destination or to find the next charging station. Range anxiety poses as a barrier in the shift from conventional internal combustion engine vehicles to EVs. "Charger confidence" is a term used to demonstrate the ability to address range anxiety.

Operational stakeholders for vehicle-grid integration

Operational stakeholders	Typical concerns and motivations
EV users • Vehicle drivers • Fleet managers	• **Concerns**: finding an available and functional charger and having enough autonomy for the next trip; privacy and security • **Motivation**: charging convenience and lower energy bills • Programmes to manage EV charging are welcome, but the ability to opt out of the programmes is necessary
EV manufacturer or vehicle original equipment manufacturer (OEM)	• Manufactures vehicles and provides warranties for components (batteries may be manufactured by a separate entity) • Dimensions the maximum charging capacities of the vehicles to ensure safety • Can install basic control and communication functionalities in the vehicle • **Concerns**: handling warranty claims; charging convenience of clients • May engage in some programmes to support charger deployment • **Motivation**: sales and market share
Charge point operator (CPOs) or battery-swap station operator	• Operates and often also owns the charging infrastructure • **Concerns**: securing grid interconnection and land acquisition; network tariffs • **Motivation**: business model to increase charge point utilisation and revenue streams
Electric mobility service provider (EMSP)	• As the interface between the EV user and the CPOs, ensuring accessibility to electricity recharging • EMSPs may be associated with a CPO or have arrangements with several CPOs to expand access for the user • Some original equipment manufacturers may have extended services similar to that of an EMSP • **Concern**: interoperability of charge points for users • **Motivation**: business model to maximise share of subscribers
Network/system operators	• Regulated monopolies operating the transmission grid (transmission system operators, transmission network operators or transmission network service providers) and the distribution grid (distribution system operators, distribution network operators or distribution network service providers); distribution companies are also in charge of metering • **Concerns**: maintaining grid security and quality of electricity supply • **Motivation**: obtaining revenue from public service provision under regulatory constraints
Electricity suppliers and retailers*	• Companies supplying electrical power systems; suppliers offer electricity to the wholesale market while retailers in turn buy the offered energy and sell electricity directly to the consumers • **Concerns:** retailers have concerns about balancing their portfolios and ensuring that retail rates pay for the purchased energy; suppliers, especially of variable renewable energy, have concerns about securing a buyer/off-taker to help reduce financial risk
Aggregators	• Third-party entities that help aggregate various distributed resources, through EMSPs or CPOs, to act as middlemen to provide services to the power system; some retailers can also act as aggregators • **Motivation**: obtaining access to services where they can offer their contracted resources

* In most advanced economies, the power sector is unbundled and restructured, and companies such as generators and retailers compete in the market. In other countries or subnational systems, regulated vertically integrated monopolies remain the norm. These vertically integrated markets conduct similar activities of generation, transmission, distribution and retail but may be organised in a different manner within a company.

For planning stakeholders, a main focus on co-ordination is needed. Given that most EVs are recharged while they are fully parked, the planning of locations for public charging infrastructure will involve local authorities, urban and transport planners, and the building sector. Moreover, charging programmes that shift charging to more favourable times in a 24-hour period to reduce the peak load or increase the consumption of renewables will require the co-operation of electric vehicle supply equipment (EVSE) manufacturers, battery manufacturers, researchers and regulators to establish technical requirements.

Planning stakeholders for vehicle-grid integration

Planning stakeholders	Typical concerns and motivations
National and local authorities	• Deploy policies to enable and support the shift to electric mobility • Facilitate access to public spaces for charging in municipalities or at highways, and to private spaces through building regulations for charging provision • Can serve as focal points for co-ordination with network operators, urban and transport planners, and charge point operators • Local authorities may not always have expertise in EV charging
Energy regulators	• Agencies tasked with regulating network monopolies and ensuring competition in non-monopolistic activities; even though independence is preferred, these can exist as functions under the energy ministry • **Motivation**: ensuring consumer welfare through fair tariffs and service reliability
Battery manufacturers	• Develop and innovate on battery technology; they possess expertise in battery handling and safety, power limits and degradation dynamics • **Concern**: availability of materials, especially for lithium-ion batteries • **Motivation**: battery sales to vehicle original equipment manufacturers or subscriptions via battery-as-a-service
EV supply equipment manufacturers	• Provide the equipment for charging: portable or fixed electric vehicle supply equipment to EV users and charge point operators • **Concern**: compatibility of electrical and communications features with vehicles, charge point operators, electric mobility service providers and the power system
Urban and transport planners	• Identify mobility needs for people and goods and routes to efficiently fulfil these needs; may have the expertise to determine locations for installing charging points from the user perspective • **Motivation**: providing efficient solutions for transporting people and goods that may go beyond electric mobility
Building sector • Real estate • Construction	• Similar to local authorities, may be instrumental in giving access to spaces for EV charging to complement the current role of providing space for vehicle parking • **Concern**: determining electrical connection requirements for EV charging that may exceed their typical allocated capacity or increase their typical network tariff
Research institutes and think tanks	• Conduct research on key technological and business aspects of electric mobility • Can conduct pilot studies and demonstrations to help inform policy and business models • Can develop expertise in modelling EV uptake and determining system impacts

Create multidisciplinary working groups on electric mobility

The first step for policy makers is to create working groups on electric mobility to bring together different stakeholders to arrive at common objectives, such as supporting EV uptake or minimising the total energy system cost. For example, supporting EV uptake by developing right-to-charge laws that allow tenants in multi-unit-dwelling households to install charging points, or the expansion of rights-to-connection that can allow parking lots to request connections from the grid, will require engagement with these different stakeholders.

Working groups help gather working-level officials from the sectors involved and create a focal point for knowledge sharing and capacity building, as well as identifying the relevant contact persons. The development of robust EV uptake scenarios can also take place, along with assessments of alternative solutions under commonly agreed holistic economic frameworks.

Specific working groups related to vehicle-grid integration, such as in California, can also provide further insights into effective ways of obtaining value from EV flexibility.

1.2 Break silos in planning and policy making

In addition to engaging stakeholders, policy makers also need to co-ordinate planning and policy making across different sectors of the government. There are several opportunities for synergies, especially in the transport and energy sectors:

- Synchronising the increase in targets for EV uptake and variable renewable energy generation. Variable renewable energy generation can be increased if additional flexibility from EV batteries is leveraged. Likewise, EV uptake can be accelerated if revenue sources exist when providing flexibility for the power system.
- Co-ordinating the roll-out of charging infrastructure with transmission expansions to support the high-powered charging expected along highways. Transmission expansion along highways could also be linked to local variable renewable energy generation to reduce grid losses.
- Anticipating potential land use issues from grid extension by co-ordinating planning for grids and bus or truck depot electrification. For example, a depot of 90 electric buses requires about 4 MW of charging power and entails co-ordination between e-bus procurement and infrastructure planning, especially for additional substation needs due to the high costs of financing and risk.
- Alignment and rationalisation of incentives. Co-ordinating the taxation of internal combustion engine vehicles or fuels with electricity taxation and electric mobility incentives or charging programmes can improve the overall cost of ownership for users and accelerate the shift to electric mobility.

Alignment to be pursued among policy-making silos

	Transport and infrastructure stakeholders	**Energy and power sector stakeholders**	
Overarching policies	EV uptake targets Transport emission reductions Energy efficiency targets	Variable renewable energy penetration targets End-use electrification targets Energy efficiency targets	**Overarching policies**
Countrywide infrastructure	Charging infrastructure roll-out programmes Accepted charging standards Roaming and long-haul travel arrangements	Need to reduce peak-demand increase Balancing variable renewable energy Rising transmission cost	**Bulk power system and transmission network**
Mobility, land use and urban planning	Charging depot requirements Local mobility plans (e.g. public and active transport)	Local network reinforcement Substation or city-level infrastructure	**Distribution network and local utilities**
End users	Fuel prices including taxes and levies	End-user electricity rates including taxes and levies Smart energy offerings	**End users**

Note: End users include consumers, self-generation and storage.
Source: Reproduced from Clean Energy Ministerial (2020), Electric Vehicle and Power System Integration: Key Insights and Policy Messages from CEM Initiatives.

Establish co-operation at the policy-making level

Co-ordination on setting high-level targets for power system and transport development by senior policy makers in government departments and ministries can help set the precedent for co-ordinated planning in their respective sectors.

Co-operation can also be formalised at the institutional level. For example, the Joint Office on Energy and Transportation in the United States has been created to co-ordinate planning between the energy and transport departments to ramp up electric mobility. It was created as part of the country's Bipartisan Infrastructure Law in 2021 to boost investment in infrastructure. By utilising the transport department's rights-of-way,[4] the necessary grid expansions to power charging corridors could be accelerated through streamlined permitting and construction.

Designate contact persons in charge of cross-sectoral co-ordination

In situations where formal co-operation may not be possible, policy makers can designate contact persons to facilitate co-ordination among the different sectors. Training can ensure that these contact persons have an understanding of the

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[4] A right-of-way is a right to establish and use a pathway over a piece of land for transport purposes without necessarily owning the land itself.

planning and policy-making practices of the other sectors and can leverage the synergies in their own sectors.

Joint Office on Energy and Transportation, United States

The United States has established an institutional means to break the silo between the Department of Transportation and the Department of Energy. With a USD 300 million budget, the joint office is expected to carry out work within nine focus areas:

- technical assistance on the deployment, operation and maintenance of zero emissions charging and refuelling infrastructure; renewable energy generation; and vehicle-to-grid integration
- data sharing of installation, maintenance and utilisation for the charging and refuelling network build-out
- national and regional study on charging and refuelling needs and deployment factors for community resilience and EV integration
- training and certification programmes
- programmes to promote renewable energy generation, storage and grid integration
- high voltage and medium voltage transmission pilots in the rights-of-way of the interstate highway system
- research, strategies and actions to further reduce transport emissions
- development of streamlined utility accommodations policy for high voltage and medium voltage transmission rights-of-way
- other areas that the Department of Energy and Department of Transportation may jointly deem as necessary.

Source: Joint Office of Energy and Transportation.

2. Assess the power system impacts

Electric vehicles (EVs) interact with the power system whenever they are connected to a charging point. Like many other electrical loads, EV charging can cause operational challenges and require upgrades based on the power drawn from the system and the specific location from which the power is drawn. The impacts can be classified as those affecting the capacity limits of the different components of the network, those that affect the power quality for the end users and those that affect the larger power system.

- **Line, transformer, and feeder loading**: sustained loading beyond the physical capacity of the components of the grid can lead to premature ageing or permanent damage. Operating limits on current, voltage, frequency, temperature and losses are placed in order to reduce the likelihood of this problem. The components must be upgraded or reinforced if loading is expected to regularly exceed these limits.
- **Power quality**: the current drawn for EV charging may lead to imbalances[5] in the network voltage if EV charging is done on a single phase and may also lead to harmonic distortions. Lower power quality could lead to the eventual damage of other nearby electrical appliances, and hence distribution utilities are subject to power quality indicators, such as contractual voltage limits and harmonic distortion limits.[6]
- **Systemwide impacts**: charging during peak periods can exaggerate the peak demand and the subsequent need for peak generation capacity.

The extent to which these grid impacts manifest depends on the charging use cases that develop and where they occur, which in turn are based on the electrification of vehicles. Defining an electric mobility strategy is the first step in assessing the grid impacts resulting from transport electrification.

2.1 Define an electric mobility strategy

Vehicle segments provide insights into charging needs

Countries have differing existing vehicle types due to a complex set of factors involving their geography, structures, purchasing power, local economic activities

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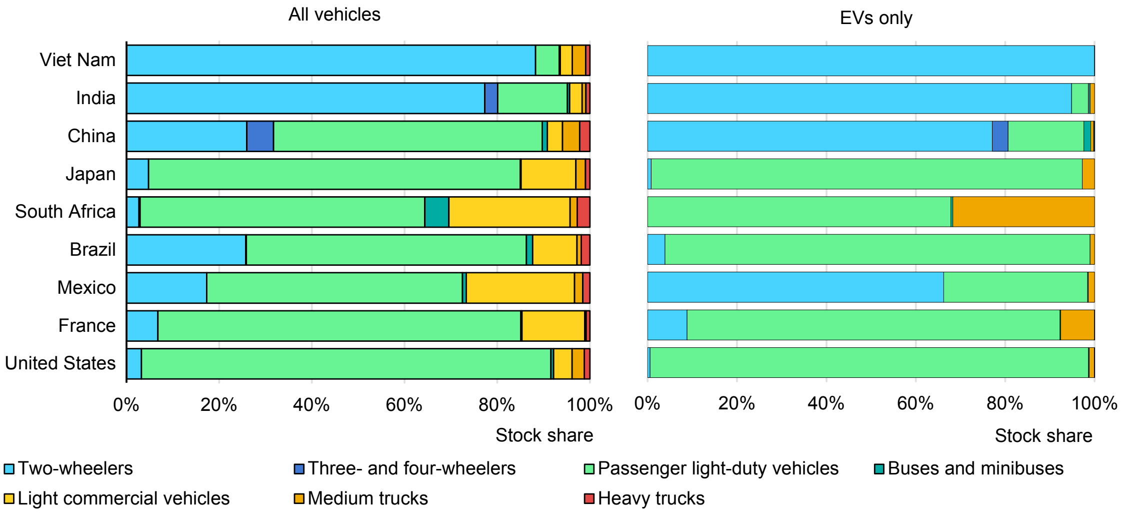
[5] To maximise the efficient use of the equipment, power systems are made of three symmetrical phases. The network operator ensures that the phases remain more or less symmetrical by avoiding the current drawn from one phase significantly exceeding that of the others.

[6] Recommendations to resolve power quality issues are increasingly being addressed in international technical standards that policy makers can directly implement. The policy manual would focus on the wider techno-economic impacts of EV charging that involve decisions on network and generation capacity.

and local mobility preferences, among other factors. Policy makers can conduct a first-level classification based on the broad vehicle type to understand the expected power system impacts of charging.

- **Two-wheelers and three-wheelers** generally have small battery capacities (0.5-20 kWh). They can be charged using a regular socket through a portable charger, or their batteries can be swapped. They usually do not have active cooling systems, so high-power charging is limited. The power demand is comparable to washing machines (0.5-1.5 kW) and room air conditioners (3-4 kW).
- **Light-duty vehicles** have a wide range of battery capacities (10-100 kWh) and comprise different sub-classes, such as plug-in hybrid electric vehicles and full-battery electric vehicles.
- **Light commercial vehicles** are vans and small pickup trucks with battery capacities in a similar range as light-duty vehicles (35-76 kWh).
- **Buses** have a range of battery capacities (50-550 kWh) depending on the specific vehicle use, with smaller batteries being associated with trolleybuses where certain sections can be connected by catenary wiring.
- **Trucks** have high battery capacities (100-800 kWh) due to the long distances and high power requirements.

Stock share of all vehicles (left) and EVs (right) by vehicle type in selected countries



IEA. CC BY 4.0.

Note: Four-wheelers or quadricycles are small car-like vehicles. They are grouped with three-wheelers and separated from larger-volume passenger light-duty vehicles or sedans.
Source: IEA analysis from IEA Mobility Model.

Note that there can be considerable variation across markets in battery capacity, vehicle power and energy efficiency that can change the power and energy requirements of different vehicle classes. However, a more significant factor to consider is the vehicle use case.

Classifying vehicles according to the **vehicle use case or vehicle segments** can reveal route patterns and dwelling times. These are used as guides for battery sizing and charging infrastructure planning, with the aim of minimising total system costs. The resulting charging roll-out plans provide an idea of the location and charging profile of the surrounding connected load, which then inform about the impact on the grids.

Typical charging solutions for selected vehicle segments

Vehicle class	Vehicle segment	Driving patterns	Charging solutions
Two-wheelers	Personal	Regular patterns of home to workplace with occasional travel for leisure	Home charging and destination charging (0.5-3.3 kW), battery swapping
	Taxi or ride-hailing	Diverse routes with high daily mileage and off-shift charging at depot or home	Public charging (0.5-3.3 kW), battery swapping
Three-wheelers	Taxi Last-mile delivery	Diverse routes with high daily mileage and off-shift charging at depot or home	Depot, home and public charging (0.5-3.3 kW)
Light-duty vehicles	Personal	Regular patterns of home/roadside to destination (workplace or leisure) with occasional long-distance travel	Home charging (1.9-7 kW), destination (workplace or leisure) charging, public charging (≤22kW), en route/highway fast charging (50-350 kW)
	Taxi or ride-hailing	Diverse routes with high daily mileage and off-shift charging at depot or home	En route fast charging (50-350 kW), depot charging (≤22-350 kW) and home charging
	Car sharing	Diverse routes with regular stops at planned locations	Public charging (≤22 kW)
Light commercial vehicles	Last-mile delivery	Diverse routes with stops at depots	Depot charging (22 kW)
Buses	Intracity or transit bus	Fixed routes with pre-determined schedules and short stops during the day	Opportunity (bus stop) charging (150 kW or more) and depot charging (22-50 kW)
	School bus	Semi-fixed routes with daytime parking at the school	Destination (school) charging (19-50 kW)
	Regional bus	Fixed long routes along highways with fewer stops	En route fast charging and depot charging (50-350 kW)

Vehicle class	Vehicle segment	Driving patterns	Charging solutions
Trucks	Local distribution	Diverse routes with stops at depots	Depot (19-125 kW)
	Regional or long-haul delivery	Semi-fixed long routes on highways with mid-shift stops and off-shift charging at depots	Depot (<350kW) and en route megawatt charging (1-3.75 MW)

Notes: Charging levels and standards vary by country and region. A detailed comparison is provided in the Annex. EV battery charging is conducted via DC through an onboard AC-to-DC converter. The capacity of the onboard charger limits the speed and power coming from the socket and is usually in the range of 3-22 kW. For DC charging, the battery is charged directly from the charging infrastructure equipped with the rectifier.

Sources: IEA analysis of AEEE (2020), Charging India's Two- and Three-Wheeler Transport; Basma, H. et al. (2022), Energy Consumption and Battery Sizing for Different Types of Electric Bus Service; Borlaug et al. (2022), Charging Needs for Electric Semi-Trailer Trucks; Borlaug, B. et al. (2021), Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems; ChargeUp (2022), State of the Industry; ENTSO-E (2021), Electric Vehicle Integration into Power Grids; Gao, Z. et al. (2017), Battery Capacity and Recharging Needs for Electric Buses in City Transit Service; Link, S. and P. Plötz (2022), Technical Feasibility of Heavy-Duty Battery-Electric Trucks for Urban and Regional Delivery in Germany—A Real-World Case Study; NACFE (2021), Box Trucks: Market Segment & Fleet Profile Fact Sheet; NITI Aayog (2021), Handbook for Electric Vehicle Charging Infrastructure Implementation; NREL (2021), Electrifying Transit: A Guidebook for Implementing Battery Electric Buses; RAP and ICCT (2022), Electrifying Last-Mile Delivery; Rojas, J. et al. (2022), Caso Mi Taxi Eléctrico y las Barreras para la Electrificación del Transporte Público Menor [The Case of Mi Taxi Eléctrico and the Barriers to the Electrification of Minor Public Transport]; SEPA (2021), The State of Managed Charging in 2021; Turoń, K. and G. Sierpiński (2018), Electric-Car-Sharing in Urban Logistics – Analysis of Implementation and Maintenance; UITP (2020), The Case for Electrification of Taxis and Ride-Hailing; US DOE (2022), Electric School Bus Education; US DOT (n.d.), Electric Vehicle Charging Speeds (accessed 1 March 2022); Vosooghi, R. et al. (2019), Shared Autonomous Electric Vehicle Service Performance: Assessing the Impact of Charging Infrastructure; ViriCiti (2021), Opportunity Charging for E-Buses.

The charging infrastructure roll-out plans also provide an opportunity for the power system planner to determine the eventual power and energy requirements of vehicles that have been electrified. In the IEA's Policy Brief on Public Charging Infrastructure, co-ordinated planning and collaboration are identified as important steps, especially when identifying locations with available grid capacity.

Understand key mobility needs and challenges

The first step in defining an electric mobility strategy is to understand the mobility needs for both passenger and freight purposes. This involves identifying the most efficient pathways for transporting people and goods between points and through corridors. There are several analyses and management toolkits that exist, and transport policy makers have the relevant expertise to conduct such analyses. Using avoid-shift-improve principles can help make overall transport sustainable.

An important aspect to consider is that replacing the current vehicle stock with EVs may not always be the best solution for the challenges faced. For example, in high population density areas with frequent congestion, shifting portions of passenger mobility to public transport and active transport (i.e. cycling and walking) can be a better solution for improving the traffic flow for the remaining on-road passenger and freight vehicles. Options such as bus rapid transit can be efficient and competitive and can also pave the way to electrification. Electrified public transport, such as metros, trams, and trolleybuses, are already common and provide a solid experience base.

For example, in the electric mobility strategy of Saanich, Canada, the individual motorised vehicle share of mobility is expected to decrease from 77% in 2017 to

50% in 2050, while that for public transport is projected to grow from 10% to 20%, respectively. Likewise, the London Mayor's Transport Strategy and the London Environment Strategy target a mode shift to walking, cycling and public transport from 64% in 2018 to 80% in 2041 and require vehicles to be zero emissions by 2030 for light-duty vehicles and 2040 for heavy-duty vehicles.

Determine vehicle electrification priorities

There are several ways policy makers can prioritise the electrification of vehicle segments. These include prioritising them based on the electric mobility benefits they wish to enable, such as GHG emissions reduction, local air quality improvement, and fuel import reduction.

In Mexicali, Mexico, key considerations for prioritising vehicle electrification include the potential to reduce GHG emissions, reduce noise, and improve local air quality. The report has also considered the prioritisation of fleets to help generate a critical mass of charging infrastructure and identified light-duty vehicle taxis and transit buses as candidates for electrification.

Affordability and current usage patterns can also be major considerations. In many Latin American countries, buses form a significant part of daily travel, with significant numbers in Colombia and Chile. The transition towards bus electrification has been fast as e-buses have reached cost parity with diesel buses in certain instances as a result of lower operations and maintenance costs and better financing availability.

Likewise, the total cost of ownership for two-wheelers for personal use, ride-hailing and last-mile delivery is lower compared to internal combustion engine equivalents. As such, countries with significant shares of two-wheelers have high targets for electrification. For example, In Indonesia, the 2030 target is 13 million electric motorcycles compared to 2 million passenger light-duty vehicles.

Chile's electromobility strategy

Chile's electromobility strategy sets the main strategic guidelines, actions and targets for sustainable transport in the country. The strategy was developed through a participatory process with stakeholders and is aligned with the broader long-term energy policy to 2050.

The strategy contains specific outputs for the expansion of charging infrastructure; infrastructure and regulation; R&D and capacity building; and information, co-ordination and international co-operation. The objective is for electric mobility to contribute 20% of the emissions reduction effort required to reach carbon neutrality by 2050.

In the past five years, Chile has embarked on a rapid increase in deploying EVs in the capital Santiago and has set ambitious targets for electrifying road transport nationwide over the coming decades:

- **By 2035**: 100% of new additional urban public transport, 100% of new sales of light- and medium-weight vehicles and 100% of new sales of agricultural and industrial vehicles with power output greater than 560 kW.
- **By 2040**: 100% of new sales of agricultural and industrial vehicles with power output greater than 19 kW.
- **By 2045**: 100% of new sales of land cargo transport and inter-city buses.

The strategy also outlines various requirements for the charging infrastructure, grid integration and regulation.

Expansion of charging infrastructure

- Preparation of a national plan of reference locations for charging points based on vehicle flow and power grid availability criteria.
- Preparation of a best practice guide covering technologies and business models for local governments.
- Identification and reduction of hurdles to the installation of public charging infrastructure.
- Using public tenders to leverage investment in highway charging solutions.
- Shortening interconnection timelines for charging stations through a web platform.

Grid integration

- Assessment of mechanisms to encourage off-peak charging to avoid power grid congestion and stress.
- Creation of active co-ordinated planning between planning new charging hubs, public transport and grid planning to shorten design and implementation timelines.
- Incorporation of a grid communications component into the charging infrastructure to enable future bidirectional charging and other power system services.

Regulatory framework

- Enforcing interoperability to facilitate access and connection to the charging network.
- Development of technical standards for the charging infrastructure.
- Regulation of existing and new buildings to include spaces for charging infrastructure.

Source: Government of Chile (2022), National Electromobility Strategy.

2.2 Gather data and develop insights

Undertake travel surveys

Determining typical vehicle use, daily travel and parking preferences through travel surveys can give huge insights into likely EV driving behaviour. Longer daily travel, such as for taxi segments, can require larger battery capacities and/or more frequent charging. Travel surveys can also provide insights into whether expanding electrified public transport, such as rail or buses, could be more cost-effective and impactful. For example, multiple paths along common routes can be an opportunity for public transport instead.

Household travel surveys can form a solid basis for modelling, as has been validated for Switzerland. Such surveys can be coupled with EV registration databases, which take vehicle model specifications into account and provide insights into new sales and second-hand use. Travel surveys are already deployed in most advanced economies and in countries such as Chile and Thailand.

As the electrification of transport progresses, however, the travel patterns of EVs can deviate from those of internal combustion engine vehicles. More precise information from EV users on their travel routes and charging patterns can help develop holistic insights for policy makers. More tailored surveys targeting EV users, such as that conducted by Enedis in France, can provide a better understanding of charging needs.

Leverage digital technologies

Digital technologies, such as GPS data, can give information on specific travel routes and corridors and aid in the specific placement of charging infrastructure. In Europe, a GPS-based study found that the share of the private fleet in motion at the same time never exceeded 12%, with some areas as low as 5%, indicating the massive grid-integration potential of electrified private mobility. Likewise, in the United States, the National Renewable Energy Laboratory created models to project the need for slow and fast charging, with considerable accuracy on the miles travelled based on GPS data and travel surveys. While personal vehicle users may have data security considerations regarding GPS, public and commercial uses, such as buses, trucks, ride-hailing and delivery vans, could provide immediately actionable insights for the choice of charging locations and grid development. For example, regionwide GPS studies on truck travel in Europe show multiple stops at rest areas of less than 3 hours, followed by stops of 8-23 hours at logistics hubs.

Record charging session data

Analysis of charging patterns can help improve information on actual connection and charging times, uncover flexibilities and inform charging infrastructure deployment strategies. For example, charging patterns between plug-in hybrid electric vehicles and battery electric vehicles vary, with higher variability observed in the former.

For public charging infrastructure, cities and municipal authorities can specify the data-sharing requirements in their tenders to facilitate early access to charging data. Opening access to collected data, especially on type, quantity, location, availability and utilisation, can help planners and researchers determine whether the charging points are accessible and reliable. The recording of charging sessions can be initiated by EV associations, such as in Norway, or collected by public authorities, such as in Germany.

For home charging, policy makers could require onboard meters or data sharing from vehicle telematics systems, coupled with data privacy regulations. In major EV markets where the majority of charging occurs at home, data from public charging sessions may miss information on the time periods of electricity use. Obtaining information directly from vehicles can be an alternative pathway. There are already regulations, such as the On-Board Fuel Consumption Meters in Europe, that aim to improve the accuracy of data on actual emissions from internal combustion engine vehicles and plug-in hybrids by placing onboard tools for the real-time measurement of energy consumption. Extending these regulations to EVs can reveal time periods of connection and charging. Data from vehicle telematics systems installed by several OEMs can already provide information on periods of battery recharging.

Given the potential sensitivities related to personal information involved in home charging, data collection efforts require extensive stakeholder discussions to balance the value of gaining insights with the data-sharing risks to develop appropriate data protection measures. General data protection regulations, such as those developed in the European Union, can help in establishing trust by allowing data providers (in this case EV users) to view their personal data and object to their use and processing when needed.

Maintain open access to public charging infrastructure data

Researchers and private companies can use open access to help leverage their collective efforts in analysing the effectiveness of charging services. They can also help recommend the placement of charging infrastructure in consideration of transport corridors, municipal zones, and grid capacity. Examples of open EV load data in major EV markets can serve as reference for policy makers looking to develop open datasets.

Run pilot studies

Pilot studies can help provide in-depth insights, especially for identifying specific charging needs within local mobility contexts. Early efforts, such as the EVI Global EV Pilot City Programme under the Clean Energy Ministerial, offered experiences from frontrunner cities. Ongoing pilot studies, such as SOLUTIONSplus, incorporate integrated mobility solutions. Meanwhile, recently launched pilot studies, such as SCALE and EV4EU, aim to develop knowledge on vehicle-grid integration.

2.3 Assess grid impacts based on mobility scenarios

Grid impacts and opportunities vary by charging use case

Based on the charging solutions selected for the electrification of vehicle segments, the grid impacts and opportunities can be classified according to the charging use cases that the vehicle segments take up.

Grid impacts and opportunities for charging use cases

Charging use case	Impacts	Opportunities
Home charging	Overloading issues expected for high levels of EV penetration* with high levels of simultaneity** and voltage issues for rural areas.	Off-peak charging or reduction of variable renewable energy curtailment via load shifting depending on connection time duration and charging time.
Workplace and destination charging	Lower probability of overloading issues due to larger capacities typical in commercial or industrial zones.	• Potential increase of consumption of solar generation due to typical daytime connection. • For the workplace: flexibility potential can be facilitated by a fleet manager, especially for workplaces. • For destination charging: flexibility potential might be limited depending on the dwelling time.
Public roadside charging	Similar issues to home charging, especially with higher power draws from three-phase charging.	Similar flexibilities possible for destination and home charging. However, strategies to increase utilisation by encouraging car-switching once fully charged may limit the potential.
En route charging (also called opportunity or top-up charging)	Potential high-power draw. Depending on the power and volume required, dedicated transformer or stationary storage serving as a buffer might be required.	• Limited demand response flexibility due to short or non-existent surplus connection time. • Higher power system participation may be possible if buffer storage is installed.
Depot charging	• Expected high-power draw due to larger volumes and numbers of vehicles served. • Dedicated substation might be needed, but the added cost can remain viable due to the nature of the commercial operation. • Network upgrades might encounter land use restrictions, especially if located in dense urban areas.	• Fleet predictability and load management offer high potential for load shifting, variable renewable energy, curtailment reduction and bidirectional charging due to larger battery capacities and existing fleet control. • Flexibility potential might be limited to a few hours depending on the parking period and trip scheduling.

Charging use case	Impacts	Opportunities
Battery swapping	- Limited overloading issues due to charging control within the battery-swap station. - May require dedicated feeders depending on the station size.	Full 24/7 bidirectional interaction with the grid and the aggregated capacity could facilitate renewable energy offtake. Battery charging management can help reduce asset ageing.

* EV penetration can be defined as the share of current vehicles converted to EVs, or the amount of EVs per dwelling.

** Simultaneity is the coincidence of EVs resulting in a higher collective charging power and is very dependent on local conditions. In China, studies estimate 21% coincidence for residential neighbourhoods, 15% for workplace charging and 5% for charging in leisure or commercial spaces. In Germany, the simultaneity factor can vary between 30% and 40% for a set of 100 public charging points, meaning that for areas with 100 charging points, grid operators could expect simultaneous charging in 30-40 charging points.

Notes: There are also proposed alternative charging techniques, such as inductive charging, catenary wiring, mobile EV charging and automated conductive charging, which are at different stages of maturity. They are briefly discussed in the Annex. These require further study, especially in determining the optimal investment mix given how they could be competitive for specific use cases despite potentially higher capital costs.

Sources: US DOT (n.d.), Electric Vehicle Charging Speeds (accessed 1 March 2022); ENTSO-E (2021), Electric Vehicle Integration into Power Grids; Gao. Z. et al. (2017), Battery Capacity and Recharging Needs for Electric Buses in City Transit Service; AEEE (2020), Charging India's Two- and Three-Wheeler Transport; RAP and ICCT (2022), Electrifying Last-Mile Delivery; Barthel, V. (2021), Analyzing the Charging Flexibility Potential of Different Electric Vehicle Fleets Using Real-World Charging Data; Li, S. (2020), Optimizing Workplace Charging Facility Deployment and Smart Charging Strategies; IEA (2022), Policy Brief on Public Charging Infrastructure.

The impacts of charging may vary across locations, especially due to the profiles of other connected loads and the typical network capacities allocated to them. In residential and commercial areas, the additional load from charging EVs could aggravate the typical peak periods during the evening and daytime, respectively, due to the use of lighting, heating or air conditioning, appliances and other plug loads during the same time periods. On the other hand, the impact of additional load from EV charging may be minimal relative to existing industrial loads and dedicated network capacity.

Analysis of different distribution networks would be needed to consider these variations. In Australia, for example, analysis of urban and rural areas shows that 80% EV uptake is possible in urban areas with robust grids but can be as low as 0% in certain rural grids where the transformers are already overloaded and due for upgrade.

Model power system impacts based on EV uptake and charging profiles

Based on travel surveys and charging sessions, and in collaboration with fleet operator targets, policy makers can model the impact of electric mobility on the power system, with the help of modelling tools. Depending on the type of analysis, there are several models that can be used.

Distribution-level analyses can help determine specific issues with network capacity and facilitate planning for distribution companies to anticipate the build-out. Such analyses require more detailed information on vehicle segments, the electrification of other loads, the transport corridor, and the distribution network layout. For example, in the Netherlands, forecasts of EV uptake are developed at the neighbourhood level. These forecasts project up to the 2035 horizon and are updated every two years.

Bulk power system-level analysis, on the other hand, can reveal more state-level or national-level impacts of the aggregated load and flexibility opportunities or peak-demand challenges for power system generation planning. It can also provide a first-order estimate of the impacts of the electrified vehicle classes. In Thailand, for example, scenario analyses based on national EV targets estimate 18-35 million private e-motorcycles compared to 1.1-1.3 million electric light-duty vehicles by 2036, with peak demand driven by private electric two-wheelers up to 1 400 MW and electric light-duty vehicles up to 1 250 MW.

Create mobility scenarios to address uncertainties

There are several uncertainties in the uptake of electric mobility. Historically, shares of battery electric vehicles compared to plug-in hybrid electric vehicles have varied significantly, and average electric ranges have also increased, indicating an increase in battery capacities. Charging preferences can also change, such as when electric light commercial vehicles in Shenzhen, China, shifted to more mid-shift fast charging compared to depot charging once the fast-charging infrastructure was made available.

To account for these types of uncertainties, policy makers can create mobility scenarios that aim to model the sensitivities of different trajectories. While there are various methods that aim to incorporate varying probabilities, creating scenarios can help create a cohesive set of factors or policy targets for which the power system will be tested.

For example, in a vehicle-grid integration study on France, mobility scenarios considered varying shares of private EVs of 7-15.6 million by 2035, alongside varying shares of rail and electrified public transport and autonomous sharing of vehicles, corresponding to the forecasts and policy targets of the country.

These mobility scenarios also need to be coupled with projections of other possible trends, such as heat pump uptake, air conditioning acquisition and the uptake of distributed PV.

For example, in a US electrification futures study, varying adoption of EVs from 30 million to 242 million light-duty vehicles is modelled alongside building and industrial electrification trends to develop a model for the grid under different power supply scenarios.

In the mobility scenarios, bulk power system-level analysis can provide insights into the amount of flexibility that can be considered reliable even while considering differences in uptake. In addition, distribution-level analyses can show the locations of optimal network expansion and locations where measures to limit power would be preferred.

3. Deploy measures for grid integration

Grid integration is the process of adapting power system operations to accommodate the entry of new energy technologies in a cost-effective manner. For distributed energy resources such as EVs, the following characteristics help distribution companies determine the extent to which the resource could affect or fully participate in the system.

- **Visibility**: location information of the connected resource. For EV charging, this could entail information on the charging status of electric vehicle supply equipment (EVSE) and load profiles.
- **Control**: the ability to influence the operation of the connected resource. For EV charging, this could include the ability to send signals to start and stop charging or to modulate the power of a connected EV.
- **Guidance**: the ability of the network operator to provide locational guidance on where the connection should preferably take place, taking into account the minimisation of upgrade costs or the improvement of system performance.

Based on the needs and capabilities of the distribution company, and based on the charging use cases, one or a combination of any of these features could be utilised through a set of policies.

3.1 Aim to accommodate all charging solutions but encourage managed charging

Inflexible high-power charging, such as en route fast charging or opportunity charging at bus stops, can strain the local distribution grid due to the high-power requirements and can result in power quality issues. Due to its limited flexibility, it can also increase emissions depending on the generation mix.

Fast charging can also accelerate the degradation of lithium-ion batteries, leading to larger concerns for battery recycling and supply chain planning in a country.

However, accommodating all charging solutions is important for facilitating the shift to electric mobility. Encouraging en route fast charging can help reduce range anxiety and improve the uptake of EVs. Likewise, providing high-power opportunity charging at bus stops can help reduce battery size requirements and consequently the total cost of ownership, especially for medium-distance buses.

While public fast charging currently constitutes a minor share of total charging sessions, it will continue to grow, with 4.7 million charging points expected around the world by 2030 in the Stated Policies Scenario and 5.4 million in the Announced Pledges Scenario.

In the short term, policy makers can deploy measures to mitigate the grid impacts of high-power charging. In the medium-to-long term, policy makers should consider proactively planning to provide capacity in anticipation of the connection requests.

In all of these planning horizons, policy makers should aim to maximise managed charging to reduce reliance on top-up charging and leverage the flexibility potential for the power system.

Managed charging strategies can unlock benefits

For charging use cases where vehicles are connected for longer periods of time, the charging process can be managed through different strategies. Several charging strategies, collectively termed “smart”, “managed” or “optimised” charging, could contain one or all of these named characteristics to leverage EV charging flexibility, as opposed to “unmanaged” charging.

The following measures are applicable for situations where the grid connection time is typically much longer than the pure battery charging time:

- **Passive measures.** There is no active control of users’ decisions to charge, but signals are given to shift load. For example, time-of-use tariffs can be used as a signal to prompt behavioural responses from EV users to charge during off-peak periods. Other passive measures include regulating the start/stop and power modulation capabilities of chargers. These capabilities allow for simple strategies to help avoid peak load, such as randomised delay, charging as late as possible and spreading out the charging load until the departure time.
- **Active control with unidirectional charging (V1G).** Direct control is exercised by the utility with the express consent and participation of the EV user. Charging can be stopped and started remotely and/or charging power can be modulated. Hence, more refined load shifting can be done for valley-filling, peak-shaving and variable renewable energy (VRE) integration. In addition, power can also be modulated to improve local power quality. The ability to co-ordinate with other vehicles can help avoid demand charges and avoid or delay network upgrades by maximising utilisation.
- **Active control with bidirectional charging to a building or house (V2B/H).** A vehicle can discharge energy to other consumers within its vicinity through a connection point, typically to a house or building. Similar to V1G, V2B/H can maximise the utilisation of the grid to which the house or building is connected and increase the uptake of VRE, especially if there is locally installed rooftop PV. When combined with a home/building energy management system, EVs can reduce the peak load from electrified heating and air conditioning, thereby avoiding steep increases in consumption and

reducing the user’s demand charges. Finally, this measure can provide backup electricity in case of blackouts.

- **Active control with bidirectional charging to the grid (V2G).** The vehicle can discharge energy to the distribution grid through a charging point. This can occur either through an AC- or DC-connected charger. The direct interaction with the grid means that the vehicle can participate in the electricity market through arbitrage, reserves, frequency response and distribution-level services. V2G has attracted attention, with several demonstration studies globally.

For battery-swapping use cases, similar charging directions and control are also applicable:

- **Active control with battery stations (S2G or B2G).** Battery-swapping stations can use spare batteries to provide 24/7 bidirectional flexibility. Swapping decisions are then balanced in terms of the additional costs of maintaining spares and the revenue from power system participation.

Benefits and limitations of charging strategies

Strategy	System benefits	Examples	Limitations
Passive measures	• Simple and easy to implement • Can avoid inflating the peak load	• 15-20% of EV users shifted out from any given hour and 20-30% shifted into a given hour depending on the mix of incentives and price signals (California)	At higher rates of EV penetration, a lack of co-ordination among the connected EVs could result in a rebound peak, as observed in San Diego, California*
Active control with unidirectional charging (V1G)	• More reactive compared to passive measures, without accelerating battery degradation • Load can be shifted to times when renewable energy is available • Can also provide upward frequency regulation	• Simulations show up to USD 210-660 million in costs could be saved due to avoided peak capacity and increased consumption of renewables (California) • Capacity of 6-13 GW could be freed up due to smart charging compared to uncontrolled charging in an average weekday scenario in 2035 where peak demand could reach 65 GW (France)	As the power flow is unidirectional, the utilisation of renewable energy is limited to load shifting.

Strategy	System benefits	Examples	Limitations
Active control with bidirectional charging to a building or house (V2B/H)	• Increases self-consumption of local VRE • Avoids steeper changes in consumption • Contributes to resilience	• Backup power of 19-600 hours could be achieved for a V2H with rooftop PV (United States) • V2H models have been offered as early as 2012 in Japan	Bidirectional charging is limited to the local system of the house or building. Hence, further participation of EVs in the grid is limited.
Active control with bidirectional charging to the grid (V2G)	• Contributes to frequency regulation and arbitrage • Helps expand VRE consumption	A range of net savings from EUR 2 304 per EV per year to a net cost of EUR -955 per EV per year based on frequency regulation remuneration and the additional costs of a bidirectional charger (Denmark)	Accelerated battery degradation occurs due to increased charging cycles. This needs to be accounted for in charging algorithms.
Active control with battery stations (S2G/B2G)	• Easier aggregation • Longer timespan for flexibility in the same location	Pilot cities with battery-swapping stations charging during valley hours, avoiding peak hours or lowering charging power (100 kW per station on average) and discharging to the grid for a few minutes for frequency regulation (China)	The capacity to provide flexibility is limited by the trade-off between having standby battery capacity and reducing the warehousing costs of batteries.

* Rebound peaks occur when multiple deferrable loads simultaneously draw power at the first instance of an off-peak period, causing a secondary peak period. Given the significant increase in deferrable loads, such as EVs, avoiding rebound peaks through better tariff design is being studied. New tariff designs are also proposed to limit the effects of the rebound associated with the lower tariff zones of simple time-of-use tariff designs.

Each charging strategy entails a set of technological, operational and regulatory requirements to fully activate the flexibility potential associated with it. A framework is proposed at the end of this chapter to contextualise these charging strategies within the power system conditions and EV availability where they may be best suited.

Unlocking V2G through battery degradation models and vehicle durability regulations

A previously identified barrier to the commercial roll-out of V2G was the absence of a consensus on how to account for accelerated battery degradation as a result of increased cycles from bidirectional charging as well as the revocation of warranties by most OEMs if the battery was used for reverse power flow. Recent developments have been made since.

V2G will soon be compatible with OEM warranties. The United Nations Global Technical Regulation No. 22 has incorporated the use of virtual mileage to account for the additional cycles due to V2G operations. This virtual mileage can be considered as part of the mileage warranties by OEMs, hence avoiding issues on warranty revocation. The regulation will come into effect after adoption by the national legislative bodies.

Insights into battery degradation are also growing. Reviews of degradation models suggest some common trends:

- Battery degradation depends on the battery chemistry. V2G activities show an accelerated capacity fade for lithium nickel-cobalt-aluminium (NCA) batteries but a decelerated one for lithium-iron-phosphate (LFP) batteries compared to regular charging and use patterns in a year.
- The ambient temperature, especially high temperatures, can accelerate degradation.
- Degradation dynamics are sensitive to the type of service. In bulk energy services, degradation accelerates due to the large energy throughputs. Meanwhile, in fast reserve service where energy throughput is smaller, the resulting depth-of-discharge is the main factor that accelerates degradation.
- Degradation speed is a function of the state of charge. High average state-of-charge levels accelerate degradation.
- The high frequency of the V2G service is a significant contributor to battery degradation but to a lesser extent compared to calendar ageing at high state-of-charge levels.

Due to the sensitivities surrounding battery degradation, indicators such as state of health or optimal state of charge can be measured and incorporated into algorithms to reduce degradation. For example, pilot studies in the United Kingdom used algorithms to improve battery life by 8-12% through V2G operations compared to uncontrolled charging. Further research developments will help address the concerns of EV users by providing fair compensation for V2G participation.

Several measures exist to mitigate and influence connection

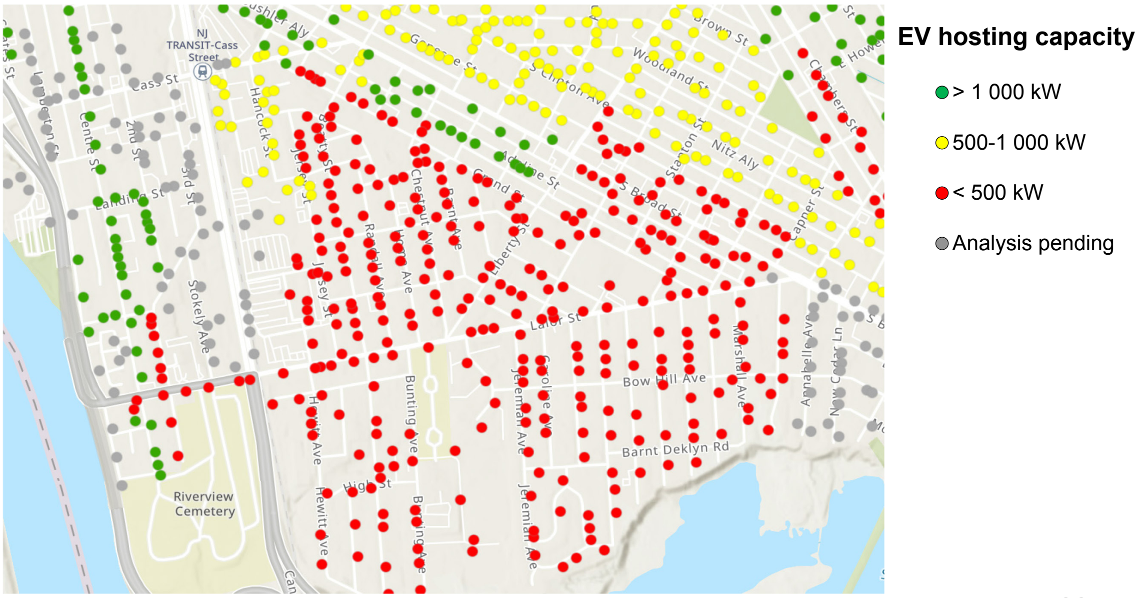
Provide locational signals for available grid capacity

One way of mitigating the impacts of charging, especially for charging use cases with high power and energy demand, is to locate stations where grid capacity is abundant. This can be done by distribution companies by creating hosting capacity maps or varying connection costs by location.

Publishing hosting capacity maps helps guide CPOs in determining the optimal locations for the connection of charging stations, especially those with a high-power demand. Hosting capacity analyses consider the impact of a potential connection in relation to existing load profiles, network capacity, and performance requirements for the distribution company. Hosting capacity maps can be enabled by geographic information systems. Overlaying existing and planned transmission and distribution networks on interactive maps showing urban data, such as on buildings, parking areas and transport corridors, can help CPOs to decide on which areas to prioritise when deploying new charging stations.

Public hosting capacity maps are already used by utilities in New Jersey, New York and California to show locations where grid capacities are available and can be approved. Proactively conducting the analyses and making them public allow CPOs to prioritise the development of charging points in areas where connections would be guaranteed, thus supporting EV uptake. Hosting capacity maps also help streamline the interconnection process and facilitates co-ordinated planning.

EV hosting capacity map of New Jersey, United States



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Source: PSE&G. EV Hosting Capacity Map (accessed 3 August 2022).

Varying local connection fees based on the available grid capacity can also serve as a locational signal. By passing a portion of the costs on to the CPO, they can then make a feasibility assessment of the charging station plans given possible higher charging rates. Making the connection fees more reflective of the needs of the grid can help avoid crowding in congested locations.

Consider non-firm connections

Non-firm connections can speed up the connection of a higher charging capacity by allowing power modulation or even disconnection during critical periods. This can avoid additional investment from the grid's perspective and reduce the costs passed on to the CPO. For example, in the north of the United Kingdom, non-firm or "flexible" connections are offered as an option in the distribution access policy. The disadvantages are that this can entail lower reliability of the charging infrastructure in general and may evoke range anxiety among EV users.

Consider using buffer storage requirements or storage fees to smooth peak demand

Stationary storage can be used in charging stations to limit the impact of high power requirements on the grid, especially during critical periods. The buffer storage supplements the grid capacity that the charging stations need and may be more cost-effective and faster than grid upgrades.

Depending on the charging station's business case, CPOs can use buffer storage as a tool to avoid high peak demand charges and as a way to participate in other power system operations to obtain additional revenue from the investment.

The buffer storage may be located in a more optimal location for the grid, and the connection fees for charging stations and other users may simply incorporate the costs of the common storage component to reduce the cost burden on each user. The use of second-life batteries can also be explored as they can reduce the levelised cost of electricity by 12-41%.

Provide signals to shift towards managed charging

Network charges can also be varied based on controllability and the maximum power of EV charging. CPOs without sufficient communication with the grid could be initially charged as if they would contribute the maximum rated power during peak periods. Likewise, the fee could be lowered if flexibility could be demonstrated by the CPO. These conditions would allow the charging point installer to make an economic assessment of the cost of investing in intelligent communication capabilities and incentivise power control.

It is important to note, though, that these measures impose costs on the CPO that will eventually be passed down to the EV user. The additional costs could act as a barrier to charging infrastructure deployment and EV uptake. Balancing the cost allocation between the CPO (eventually paid by EV users only) and the grid (eventually paid by all electricity consumers) is therefore important and must be assessed carefully by policy makers and regulators. Connections that encourage flexible smart charging can improve the utilisation of the grid. This is a net benefit for electricity users, and hence a larger portion of the costs could be covered by the grid.

Consider alternative methods to mitigate high power and energy demand

Beyond the options discussed above, there are also other proposals that can help mitigate power and energy demand when network capacity is unavailable and connection is urgent.

- **Collective charging.** Collective charging aims to gather fleet operators or fast-charging CPOs to request connection to a higher voltage level that might be prohibitive to individual connections due to its higher cost. Adjusting the scheduling of charging, especially for bus fleet operators, can help lower the connection capacity required. The higher connection cost for inflexible en route charging could entail higher charging costs for users.

- **Charging hubs.** Similar to collective charging, charging hubs can be created to provide charging services to meet the demands of vehicles whose current allocated grid capacity might not be sufficient. The strategy is more applicable to fleet operations where charging can be organised and scheduled around the available capacity of the hub. Companies can also co-operate to invest in stationary storage to expand collective capacity without having to request a higher voltage connection.
- **Temporary local generation.** Local generation can also be used to help supply the charging needs of charging stations while waiting for the expansion of the network capacity. Local renewable generation paired with storage can also help reduce the carbon content of the electricity but may incur additional costs.

Hosting capacity of a distribution grid

The hosting capacity is the amount of new energy-generating or energy-consuming technologies that can be connected to the grid without compromising reliability or power quality for the other connected users. Hosting capacity studies have been commonly used by grid operators to assess and communicate the impacts of distributed PV on performance indices and acceptable limits.

Typical metrics used are the kW of load or generation connected in relation to performance metrics of the voltage level, safety and reliability, line loading and/or transformer loading. The input values are often represented based on the technology adoption rate (e.g. EV penetration or rooftop PV per household).

Several methodologies exist with varying levels of complexity that grid operators can consider to conduct hosting capacity analyses for EVs and to convey the capacity of the grid and the implications on performance for the rest of the users.

3.2 Facilitate aggregation through standards and interoperability

The larger the number of EVs available for aggregation, the larger the flexibility potential from which the power system can draw. Supporting transport electrification and ensuring that EVs, EVSEs, and the power system use common communication protocols are, therefore, in the interest of the power system stakeholders.

Standardisation and interoperability are commonly thought to improve electric mobility uptake by allowing EV users who purchase different models to maintain access to various charging points. However, this could also be extended to improving consumer choice by providing access to managed charging and bill reduction regardless of the vehicle model choice. Likewise, for the power system, this helps ensure a larger degree of aggregation for providing services to the grid.

Facilitating interoperability would require the use of common communication protocols. Protocols help standardise data flow and commands. The following are some of the main protocols needed for vehicle-grid integration:

- ISO/IEC 15118 facilitates communication between the EV and the EVSE. It sends charging parameters based on user needs and the charging profiles from the CPO. The latest update includes protocols for bidirectional charging.
- CHAdeMO is a protocol originally developed in Japan that accompanies its specific CHAdeMO plug that physically allows bidirectional DC charging.
- IEC 61850 is a group of standards defining communication protocols for intelligent electronic devices at substations. It is a foundational standard for smart grids.
- Open Charge Point Protocol (OCPP) communicates smart charging features, such as grid capacity, energy prices, local supply of sustainable energy, and user preferences. It is currently being incorporated into IEC 63110 to establish a regular international technical standard.
- Open Charge Point Interface (OCPI) supports connections between electric mobility service providers and CPOs to allow EV users to access different charging points and streamline payments across jurisdictional borders, helping support EV uptake through roaming. Among different roaming protocols[7] OCPI supports the most functionalities including smart charging. It is commonly used in the European Union.
- Open Automated Demand Response (OpenADR) communicates price and event messages between the utility and connected distributed energy resources for the purpose of demand-side management. It is more focused on exchanging information, whereas OCPP has more emphasis on control. It has a wide adoption across the globe.
- IEEE 2030.5 enables utility management of the distributed energy resources such as electric vehicles through demand response, load control and time-of-day pricing. It is commonly used in California.
- Open Smart Charging Protocol (OSCP) communicates predictions of locally available capacity to charging station operators. The current version contains use cases with more generic terms to allow integration of solar PVs, batteries and other devices. Currently, the use of OSCP is still limited.

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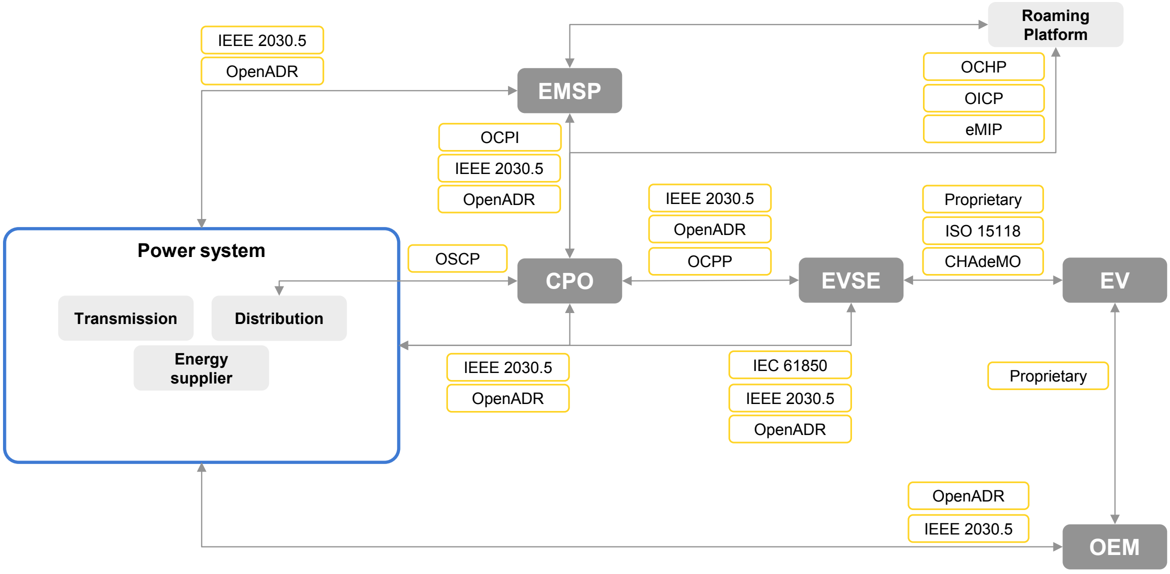
[7] Other common roaming protocols are Open Intercharge Protocol (OICP), Open Clearing House Protocol (OCHP) and eMobility Interoperation Protocol (eMIP).

Vehicle-grid integration ecosystem and communication protocols



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Notes: CPO = charge point operator, EMSP = electric mobility service provider, eMIP = eMobility Interoperation Protocol, EVSE = electric vehicle supply equipment (charging infrastructure), OpenADR = Open Automated Demand Response, OCHP = Open Clearing House Protocol, OCPI = Open Charge Point Interface, OCPP = Open Charge Point Protocol, OEM = original equipment (EV) manufacturer, OICP = Open Intercharge Protocol, OSCP = Open Smart Charging Protocol.

Sources: IEA analysis from Neaimeh and Andersen (2020), Mind the Gap - Open Communication Protocols for Vehicle Grid Integration; Element Energy (2019), Implementing Open Smart Charging; Klapwijk, P. (2018), EV Related Protocols; NAL (2021), Tendering Guidelines for Open Market and Open Protocols.

It is important to have a common communication protocol between the EVSE and the power system that is facilitated by managed charging actors. Currently, efforts are being made towards the global harmonisation of communication protocols, including those between EVs and EVSE, to aid in interoperability when crossing international borders.

Standardised communication protocols bring about systemwide benefits but can also carry risks. Using insecure protocols that lack authentication and encryption can create entry points for cyberattacks. While it is not in the scope of this manual, policy makers should conduct a cybersecurity assessment and plan for mitigation measures for charging operations.

Use incentives and regulations to set standards and interoperability

Policy makers can use a mix of incentives and regulations to disseminate key smart features. For example, in Belgium, tax deductions apply to publicly accessible charging points, and there is a EUR 1 500 incentive for residential charging points if they can be digitally connected and managed through standard protocols. Meanwhile, in Luxembourg, a EUR 1 200 incentive is given to OCPP-compliant smart charging stations. In the Netherlands, OCPP and OCPI are used as de facto standards for publicly accessible charging points based on tendering guidelines.

On the other hand, the United Kingdom's EV (Smart Charge Points) Regulations 2021 mandated that all home and workplace charging points from Q2 2022 would be required to have smart functionalities.[8] The regulations included a key rationale explaining that the market would not be expected to arrive at establishing smart interoperable standards on its own and that customers must be protected and given access to smart charging regardless of their choice of EMSP or EVSE. Likewise, in India's draft battery-swapping policy, stations are required to adopt open standard communication protocols, such as OCPP.

Legal authority on standardisation and interoperability varies by country. They can be enforced by the transport policy makers or by the economic and trade authorities.

It is important to note that the minimum standards for charging points and vehicles must make them ready to conduct smart charging but not necessarily oblige smart charging. EV users must still have the final choice to participate in managed charging schemes based on their specific needs.

Develop open vehicle-grid integration platforms as a supplementary measure

Open vehicle-grid integration platforms allow electric utilities to gain visibility and communicate demand response events to EVSEs through communication protocols and to EVs directly through vehicle telematics systems installed by OEMs.

Where homes remain the preferred location for charging, a significant portion of charging profiles may not be visible to the local utility especially if the EVSE that an EV driver uses does not have communication capabilities. In these cases, facilitating communication and control through vehicle telematics can help aggregate more vehicles to participate in the power system.

Open vehicle-grid integration platforms also allow OEMs to provide managed charging programmes as the communications go through their systems. For example, utilities in the United States, such as DTE Energy and Xcel Energy have adopted open vehicle-grid integration platforms and partnered with OEMs to use OpenADR as the common communication protocol.

3.3 Value the flexibility of electric vehicles

In order to enable the technology investments and business models that facilitate flexibility from EVs, the cost savings enabled by flexibility must be passed on to its providers. From operational requirements, such as frequency regulation, to capital expenditure savings, such as network capacity deferral, several mechanisms can be used to allow the power system to turn the cost savings into remuneration for

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[8] Smart functionalities are defined in the regulations as the ability to send and receive information and respond to signals by increasing or decreasing the rate of electricity flow through the charging point, shift the time at which electricity flows, and provide demand-side response services.

the flexibility providers. This will, in turn, allow the EV users and managed charging actors to make the necessary investments to activate grid-interactive charging.

There are several mechanisms in the market that can be used to transmit the remuneration to the EV user providing flexibility. The policy maker does not need to activate all these options, but the more they are made available, the more they can help the EV user to stack revenue from providing these services.

Market mechanisms to remunerate EV charging flexibility

Domain	Service requirement	Market mechanism
Distribution	Phase imbalance	N/A – enforced by grid code compliance
	Voltage regulation	No mature market mechanisms so far
	Congestion management	Tariffs Flexible contracts Flexibility tenders Local flexibility markets
	Fault restoration	Bilateral contracts Flexibility tenders
Transmission	Balancing and reserves	Ancillary services markets
	Energy arbitrage	Wholesale energy markets

Source: IEA analysis from Venegas (2021), Active Integration of Electric Vehicles into Distribution Grids: Barriers and Frameworks for Flexibility Services.

Tariff design

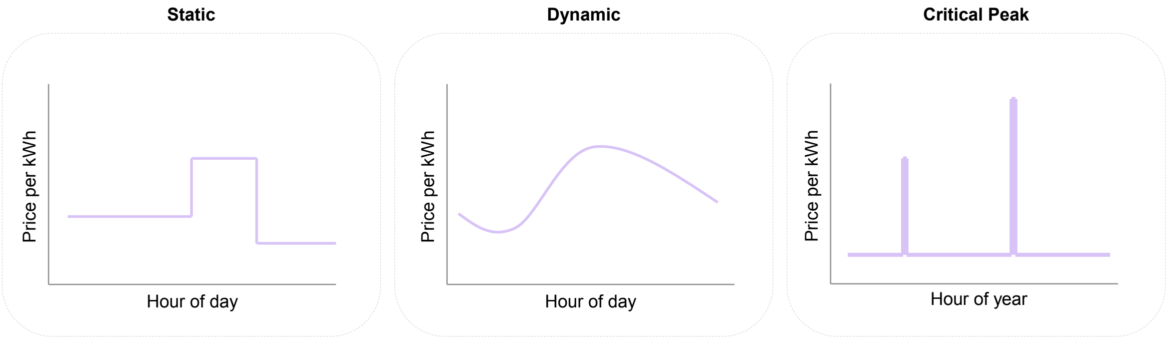
Designing tariffs in a way that reflects the cost on the grid or system based on specific time periods and locations can align the charging decisions to adapt and participate in lowering the cost for the system. These tariff designs are generally referred to as “dynamic tariffs” as opposed to flat, single-value “static tariffs”. Some of the main designs are:

- **Time-of-use (ToU) or time-of-day (ToD) tariffs.** Tariff rates can be set at a higher price to discourage load during peak periods. Rates may vary multiple times within a day, and the metering simply needs to be at the same time interval as the tariff settings (e.g., hourly). In Thailand, for example, off-peak rates can be as low as 45% of those during peak hours for connected consumers below 12 kV. In Korea, specific static ToU tariffs exist for EVs differentiated by season and the voltage level of the connection. Changes can be made more periodically – for example, using day-ahead market prices – but this implies a substantial loss of information and efficiency for the system. Enhancements to the tariff design can also be made to avoid rebound peaks while maintaining simplicity in setting up the tariff.
- **Real-time pricing.** Tariffs can be changed according to real-time conditions, especially in power grids with higher shares of utility-scale and distributed-scale variable generation where the supply-demand balance changes throughout the day and can reflect locational signals from the grid. Setting

tariffs based on the real-time conditions of the grid requires advanced metering and communication infrastructure and automation systems in order to reflect the system needs and allow the EV users to respond to the time-varying prices. While establishing real-time pricing may incur upfront expenses, it can increase the value for the system. For example, a study from the European Union shows that using real-time pricing can save up to 27% of power generation costs and reduce VRE curtailment by 14% compared to a baseline scenario.

- **Critical-peak pricing.** Tariff rates are fixed, but exceptionally high prices can be set and communicated if a load reduction is needed at specific times of the day or the year. This tariff structure is quite common and offered, in particular, for EV charging in Colorado and Southern California. Critical peak pricing in the United States is estimated to save EV users USD 1 125-1 220 per month.

Graphical representation of the basic types of tariff structure



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Provide dedicated connections for EVs if needed

The benefit of dynamic tariff designs is that they are technology-neutral and can incentivise load flexibility not just for EV charging but also for different loads. However, in certain cases, changing the tariff design can be burdensome and may require lengthy legislative changes, especially for residential loads. In this case, separating metering and creating specific dynamic tariffs for EVs as a new load category can help in facilitating EV load flexibility despite maintaining static tariffs elsewhere. In India, several states have separate EV tariffs, with states such as Maharashtra implementing ToD tariffs. Battery-swapping stations are required to participate in ToD tariff regimes with dedicated connections in India's draft battery-swapping policy. Having EVs as a specific load category can also be useful in times of shortage, helping to discriminate between the basic needs of households and more flexible electricity demand.

Allow innovative business models for engaging users

It is important that EV users and EV fleet operators are given the opportunity to contribute to power system objectives based on a set of incentives. Setting up a fair dynamic pricing model can be costly, but dynamic load shifting can also be achieved by allowing dynamic control by the utility during a certain period of the day and giving the fleet or EV user a rebate for enrolment or participation. Allowing a diverse range of possible tariff structures and reward systems can help incentivise participation from EV users.

Flexibility contracts and markets

Aside from the typical ways of accessing flexibility through network tariffs and connection agreements, market-based procurement can also be explored.

Local flexibility markets can entail bidding based on capacity and energy and enable the lowest cost of flexibility to be used first. An example is the United Kingdom, where more than 10 GW of location-specific flexible capacity was bid through a common platform where distribution network operators could publish their flexibility needs. Another example is the Crowd Balancing Platform in commercial operation in Germany, Italy, the Netherlands and Switzerland.

Bidding in wholesale markets

In countries with unbundled power markets, opening up the wholesale energy market and balancing markets to the demand side allows for the wider participation of flexible loads, such as EVs. Explicit demand-side responses allow remuneration based on the actual costs of the system, compared to tariffs, which are often fixed. However, this option may not be available, especially if the power market is only accessible to large suppliers and retailers. Hence, opening up the market to demand response and allowing the participation of entities such as EVs, charging stations and stationary batteries is a necessary first step. In instances where demand response is already allowed, the key features needed are allowing aggregation and modifying product specifications where possible to match the scale of EVs.

Allow third-party resource aggregation

Allowing third-party resource aggregation is a useful way for distributed resources to meaningfully provide services in wholesale energy markets. Aggregators can access the electricity market as participants and enter into various contracts with smaller entities providing distributed generation or load flexibility. In the United Kingdom, participation in balancing markets has been opened up to aggregators – known as Virtual Lead Parties – which allows distribution-connected assets to provide aggregate services when needed.

Adjust product specifications when possible

Market product specifications, such as minimum sizes to participate and symmetry of ancillary services products, can implicitly form barriers by dictating the minimum amount of EV aggregation needed. While the size of a product needs to be large enough to significantly influence the bulk energy system, reducing it where feasible for the system should be encouraged. For example, in several European countries, the minimum size to participate in primary regulation is 1 MW. In

Sweden, on the other hand, a minimum size of only 0.1 MW[9] is needed, meaning only 27 EVs on 3.7 kW of charging are needed to provide the required service. In the United States, 0.1 MW of resource aggregation is also accepted.

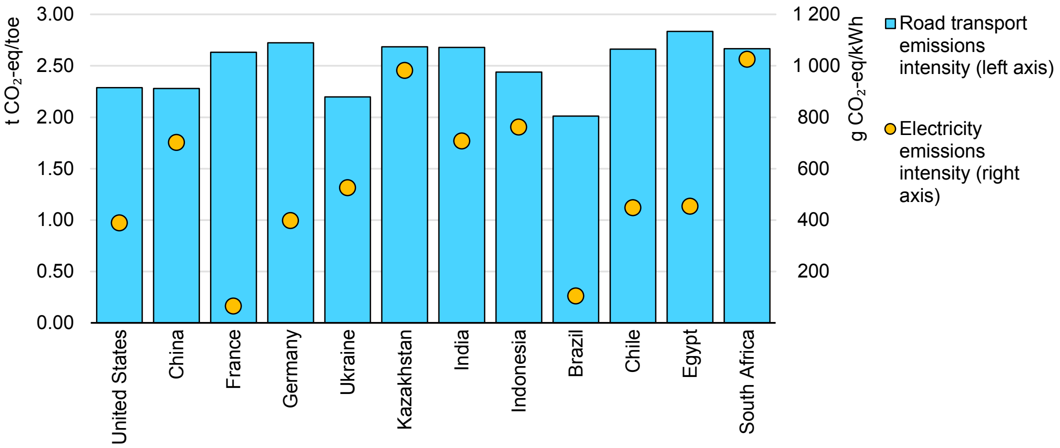
3.4 Co-ordinate EV charging with renewables

Initial demand from EV charging may increase power sector emissions

The addition of EV charging load into the power system entails a marginal generation requirement that may be fulfilled by technologies that produce more emissions. While EVs are generally considered cleaner than their internal combustion engine counterparts thanks to the higher efficiency of the conversion technology, their operating emissions are still dependent on the emissions intensity of the electricity used to charge them.

IEA analysis shows that life cycle emissions are lower for EVs compared to conventional internal combustion engine (ICE) cars only if the average emissions intensity of the electricity used to charge the EVs is less than 800 g CO_2-eq/kWh (if larger ICE cars are displaced by EVs of equivalent sizes) or less than 450 g CO_2-eq/kWh (if smaller ICE cars are displaced).[10]

Transport and electricity emissions intensity in selected countries, 2019



Source: IEA, World Energy Statistics and Balances (accessed 25 October 2022).

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[9] For normal primary regulation (power and energy), the activation time is 63% within 60 seconds and 100% within 3 minutes, whereas for disturbance (power only), the activation time is 50% within 5 seconds and 100% within 30 seconds.

[10] Small cars include battery electric vehicles with a capacity of 36 kWh (200 km range) or 75 kWh (400 km range) and internal combustion engines with a Worldwide Harmonised Light Vehicle Test Procedure (WLTP) fuel economy of 5.5 Lge/100 km. Large cars include battery electric vehicles with a capacity of 39 kWh (200 km range) or 80 kWh (400 km range) and internal combustion engines with an on-road fuel economy of 8.9 Lge/100 km. For more information, see the Global EV Outlook 2019.

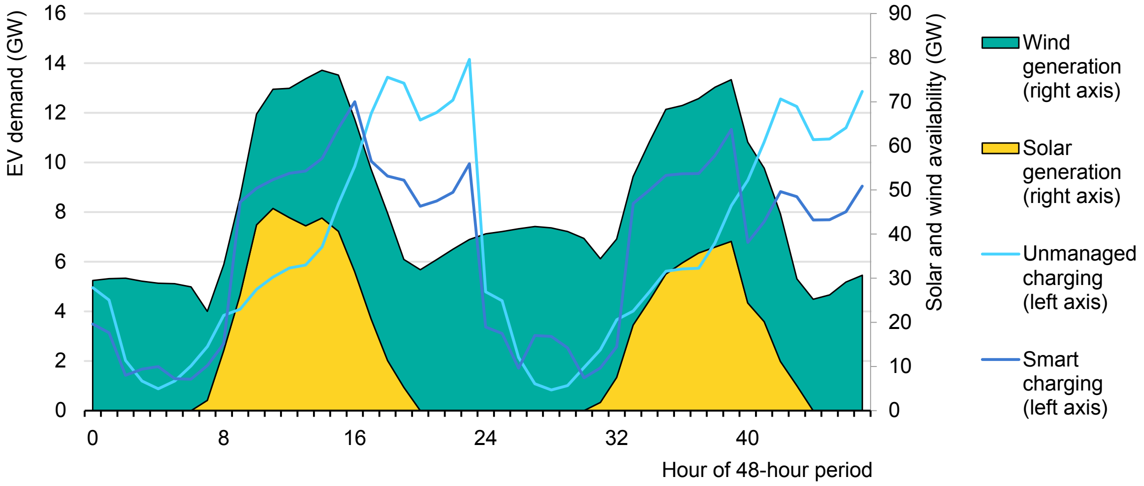
Many countries have electricity mixes with average emissions intensities[11] of less than 800 g CO_2-eq/kWh but greater than 450 g CO_2-eq/kWh, as of 2019. Hence, despite the efficiency gains from EVs, further decarbonisation of the electricity mix is needed to ensure that the transport sector also decarbonises. Fortunately, there are strong potential synergies to be gained from increasing both renewables and EVs. New electricity demand arising from electrification can be met with additional variable renewable sources.

EV charging has strong potential synergies with renewables

At the bulk energy level, load shifting of EV charging to more favourable times of the day can increase consumption and reduce the curtailment of transmission-connected renewables, leading to a better business case.

In Korea, for example, flexible EV charging of 30% of the expected EV fleet in 2035 could reduce operating costs by USD 21/MWh and peak costs by USD 18/MWh, corresponding to 21% and 30% of the costs, respectively. It could also lead to a 63% emissions reduction compared to a full internal combustion engine fleet. Matching the EV load to the availability of renewables could also provide a better business case for renewable energy developers by reducing curtailment.

Variable renewable energy patterns and the load-shifting potential of EVs in Korea, 2050



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Source: IEA (2021), Reforming Korea's Electricity Market for Net Zero.

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[11] The annual average emissions intensity of the grid is referenced here as a high-level indicator. For more rigorous accounting, the marginal emissions intensity must be considered since the exact time and location of EV charging can entail higher emissions compared to the annual average. One example is when charging occurs during peak periods where the marginal generation technology is diesel, and the network losses are high due to congestion.

There are also potential synergies at the distribution level. Currently, areas with significant penetration of rooftop solar PV can experience problems with high local voltage (overvoltage) due to the injected energy not being matched with consumption. These conditions often arise during sunny weekends when consumption is low and PV generation is high. On the other hand, simultaneous EV charging in the evening when consumption is high can cause the opposite effect of low voltage levels (undervoltage). Co-ordinating the operation of EV charging and solar PV could increase the mutual hosting capacity within a distribution grid by keeping delivery within the contractual voltage limits. For example, a modelling study in Sweden shows that the distribution grid could host a higher penetration[12] of EVs and distributed PVs when co-ordinated with a management system compared to when they are uncoordinated.

Given these potential benefits, policy makers should pursue the co-ordinated integration of EV charging to ramp up both electric mobility and the deployment of renewables. The co-ordinated plan helps ensure that the switch from ICEVs to EVs effectively decarbonises transport activity by ensuring that the marginal load imposed by the introduction of EVs can be supplied by clean electricity.

Encourage daytime charging

Daytime charging, even when unmanaged, can help increase the consumption of renewables when solar-based generation is available and reduce storage requirements and ramping costs. Vehicle segments such as personal-use vehicles and school buses tend to be parked for long periods during the daytime at workplaces or schools. Providing charging solutions in these locations helps ensure that connected EVs are available during the daytime period.

Policy makers can provide specific training for building managers to install and manage workplace chargers, as has been done in the United States, or they can also provide purchase and installation incentives, such as those available in the United Kingdom.

Provide options to contract or support a clean electricity supply

In liberalised power systems, market options for obtaining power supply from renewable sources can be developed to help increase the build-up of renewable energy capacity. Options such as consumer power purchase agreements (PPAs), green tariffs and energy attribute certificates are common options provided by countries. Green tariffs can be a suitable option for individual EV users and CPOs, whereas PPAs can be utilised by fleet managers. These options are common in Europe and the United States.

Where the mechanism already exists, high minimum size requirements can act as barriers to the types and numbers of EVs that can participate, such as bus depots or large EV fleets. Lowering the size requirements to participate, as is

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[12] For the mentioned study, the penetration rates are based on the presence of the typical load of EV charging (3.7 kW) per household and the typical daily rooftop PV output (11.4 kWh) per household.

recommended for bidding in wholesale markets, can help. For example, India recently lowered the minimum requirements for its Green Open Access mechanism to purchase renewables from 1 MW to 0.1 MW and is awaiting implementation of the regulation in individual states.

As the decarbonisation of the power system progresses, importance will be placed on increasing the precision of temporal and locational matching, such as 24/7 matching. This will require a higher frequency of exchange of information on emissions, forecasts and connected EVs. Investments in establishing a smart electric mobility ecosystem can help support this higher demand.

Develop a framework to monitor indirect emissions from EV charging

As EV charging produces indirect emissions through the electricity sector, creating a framework to monitor electricity emissions from EV charging can help align smart charging algorithms and support decarbonisation options where possible. Obtaining charging time periods coupled with the real-time and forecasted electricity mix can help align charging towards periods of lower emissions, especially in cases where carbon prices do not exist or are not significant enough to change dispatch and load-shifting decisions. Initial considerations on developing frameworks to determine the amount and share of GHG emissions from electric mobility have been conducted at United Nations Economic Commission for Europe workshops.

Leverage incentives around EV charging

Incentives for charging infrastructure deployment can be tied to renewable energy matching conditions. For example, in Belgium, to qualify for tax incentives for residential charging, the user must show that the charging point is supplied by renewable electricity through either a retail contract, an on-site renewable energy source or a mixture of both. In Hanover, Germany, between 2018 and 2021, grants of EUR 500 were given to those planning to build charging points supplied by renewable sources.

Incentives for the co-location of PV with EV charging stations can also be an option, especially for cases where distributed PV would be more cost-effective than utility-scale PV (i.e. reduced grid interconnection costs and reduced land use costs). More importantly, co-location can reduce grid losses and can offset high local EV charging demand.

System operators can identify and publish locations where co-located PV-EV charging would provide grid benefits. They can also use incentives such as rebates, special tariff structures and streamlined interconnection schedules tied to the co-location of PV and EV charging. The use of these incentives often requires authorisation from regulators and/or policy makers, depending on the regulatory regime.

3.5 Incentivise smart-readiness

Policy makers must often balance the trade-offs between instituting standards to enjoy the benefits of scale and aggregation and allowing the market to continue to innovate without additional restrictions.

Given the potential for flexibility of EVs, uncontrolled charging loads in situations where they would be parked for a long period of time represent a lost opportunity. Setting a minimum standard of communication and controllability while the EV market is still nascent will help ensure a future-proof infrastructure.

Policy makers can set the minimum requirements based on the conditions of their markets, both with respect to EV uptake and the state of the power system.

Institute randomised charging delays

Instituting charging delays based on known peak and off-peak periods can be a cost-effective solution to reduce EV load during peak periods, even in situations where EVs are connected to regular sockets. The delays should incorporate randomness and variation to prevent simultaneous power draw at the first instance of the off-peak hour that could lead to grid instability. In the United Kingdom, for example, a randomised delay of up to 10 minutes, with the remote capability of being adjusted to 30 minutes, is required in all charge points as part of the Smart Charge Points Regulations 2021.

Minimum communication requirements

Imposing minimum communication requirements on the charging infrastructure or vehicles can help ensure that more co-ordinated charging strategies can be implemented at higher levels of EV penetration.

In power systems where the grid already contains or is developing advanced metering and communications features, requiring EV charging infrastructure to be ready to communicate with the power system can help take advantage of these assets. Mandating compliance with the OCPP on EVSEs and battery-swapping stations, as has been done in the United Kingdom and India, respectively, can help ensure that the smart charging of batteries can be conducted when the opportunity arises.

In some cases, EVs may continue to charge using regular sockets or charge in areas where the distribution grid does not have advanced metering and communication infrastructure. Requiring communication features in EVs, which is already common practice for some manufacturers using vehicle telematics, can help in implementing managed charging in such contexts.

A framework for grid integration of electric vehicles

Every electricity system is unique and has specific circumstances. EVs, due to the various vehicle segments and charging use cases, also pose different types of impacts. While it is not possible to identify the level of EV charging load at which various issues will arise, it is possible to categorise the context in which EVs connect to the grid and associate measures that can be implemented to mitigate any impacts.

Given the various possible measures to manage the EV charging process, from simple to complex, determining when to deploy which measures can be useful. This report provides a framework that can be used as a guide for this. The framework summarises the key issues of grid integration:

- **Volume of flexible-charging EV load.** As EVs increase in uptake, the amount of the connected flexibility resource available when they charge can increase depending on the vehicle segment and charging use case. It is important to recognise that since the primary use of EVs is for mobility, the connected flexibility resource also entails an inevitable load from the system.
- **Flexibility demand from the system.** The flexibility demand is what remunerates the investment in the grid integration measures. The demand for flexibility can come from limitations in building new capacity or limitations in power generation during the moment of demand. For example, cost-efficiency measures on new network capacity investments can make a distribution company consider investing instead in shifting load from EVs through V1G, especially if the periods of excess demand occur for only a few hours of the year.

By examining the nature of the flexibility supply from EVs and flexibility demand, policy makers can consider the following phases to prioritise measures according to the situations they face.

Phase one

Phase one is where the EV charging load has no noticeable impact on the grid. Either the EV penetration levels are small, the vehicle segments electrified are small or the loads are small relative to the capacity of the grid. Even if there is high flexibility demand from the system, the volume of the connected storage resource is too small and sparse to be reliably utilised.

In this case, policy makers can focus on increasing the deployment of EVs through policies such as increasing charging infrastructure support or enforcing standards and interoperability to help address range anxiety or improve charger confidence. Deploying charging stations in favourable areas of the grid can be a sufficient strategy to accommodate new stocks of EVs, especially if they turn out to have limited charging flexibility.

This is a period where policy makers can focus on foundational aspects, such as developing databases for EVs and charging points and conducting data research on travel and charging patterns. From the power system perspective, an important component is creating frameworks to incentivise demand response.

Phase two

Phase two is where the EV charging load is significant and noticeable in system operations, but the flexibility demand is minimal. There is a considerable number of EVs where unmanaged charging is resulting in occasional problems in the local load or systemwide peak load. However, the demand for flexibility can remain low, either because there is sufficient network or peaking capacity in most periods of the year or there is an upcoming upgrade. Note that EV penetration may not necessarily be higher compared to phase one, but the other connected loads may also have profiles that collectively contribute to issues with the peak load or network capacities.

Applying passive measures to provide simple load-shifting measures can be a cost-effective solution. If load shifting to a defined off-peak period is specifically desired, simple signals such as time-of-use tariffs or critical-peak tariffs will be needed to obtain a response from the EV users. The signals and the response need to be measured by an hourly meter or through an onboard charging measurement device.

Personal-use vehicles and fleet operations can comprise a significant amount of the EV charging load. Hence, rallying the different entities involved in co-ordinating the charging process, such as the aggregators, CPOs, EMSPs and OEMs, will require common communication protocols and a common data exchange platform where signals can be exchanged.

Policies to encourage the self-consumption of renewables may be valuable to incentivise homeowners and building managers to schedule their EV charging to periods when on-site generation is available. In doing so, the EV charging load on the distribution grid can be reduced.

An example of a system in this phase is Norway. Despite its high share of EVs, the country can actually be classified under phase two due to its high shares of clean and flexible hydro generation and high existing distribution grid capacity, which have led to lower demand for additional flexibility from the power system. The impact of EV charging is noticeable only in certain instances, such as in winter periods, and other flexibility measures exist given that the country already has dynamic tariffs (real-time pricing) and smart meters.

Phase three

Phase three is where the flexible EV charging load is significant and there is a high demand for flexibility.

The demand for flexibility can come from local network capacity limitations wherein passive charging measures are not enough to shift the load in a more co-ordinated manner. The demand can also come from the wholesale market looking to shift a significant amount of demand to avoid marginal generation or to match renewables.

Deploying active V1G can be a useful strategy in this situation. The strategy entails enhanced communication and control, supported by advanced metering and communications infrastructure. Active V1G allows remote and co-ordinated control of charging processes based on the needs of the local distribution network or the wholesale market.

To activate this fully, grid codes should recognise V1G, and measures to value co-ordinated and aggregated flexibility should be deployed. Measures such as real-time tariffs, contracts or markets for flexibility, and opening market access to aggregators are important to allow revenue stacking for the aggregators and the contracted EVs. Forecasting generation and network capacity can help aggregators anticipate and offer EV load flexibility.

Active V1G is currently practised in the Netherlands, France and Connecticut (United States), with direct control on either the charging points or the cars themselves. EVs in these countries or states can enroll in programmes that participate in managing grid constraints and wholesale energy and balancing markets.

Phase four

Phase four is where flexibility demand is high and the availability of connected flexible EVs is also high. As the primary purpose of EV batteries is for mobility, offering up energy to the grid comes at a premium. This means that high levels of flexibility demand exist such that the market can remunerate this appropriately. Such high flexibility demand can occur in power systems relying on high levels of variable renewable energy generation, or those with limited sources of flexibility such that EVs participating through V2G become feasible.

High availability of flexible EV load is also necessary since vehicles discharge to the grid and need to be recharged according to the user's targeted state-of-charge levels. This may imply having larger batteries than the typically required range or aggregating a large pool of connected EVs such that discharging large values of energy still maintain a satisfactory state of charge at the individual level.

Island power systems tend to carry these features, especially those aiming to integrate high shares of variable renewable energy. A few V2G pilot programmes have already been conducted in the Azores (Portugal) and Hawaii (United States), and future economic viability would depend on the cost of alternative flexibility sources, such as stationary storage. Certain vehicle segments may also be better suited for V2G based on their charging periods and ease of co-ordination. For example, several V2G pilot programmes are being conducted for school buses in the United States.

For this charging strategy, grid codes should recognise V2G. State-of-health measurements help create algorithms that can properly remunerate the EV user based on the accelerated degradation (or the absence thereof) of the battery for conducting V2G services. Bidirectional protocols are also needed to activate two-way communication, and decentralised peer-to-peer power trading can help provide an additional avenue for V2G participation with other distributed energy resources. Finally, reducing or eliminating two-way taxation for storage improves the business case for V2G providers.

V2B and V2H are not included in the framework as they can be activated by the EV users or the fleet operators according to their own individual needs for backup and resilience.

Key framework considerations

- The phases are not a measure of progress, only a description of the conditions that policy makers may face in their system. Certain countries may have high levels of transport electrification coupled with sufficient network and generation capacities or the availability of other more cost-effective flexibility sources, such that flexibility from V2G (phase four) may not be necessary.
- The measures are cumulative, meaning that the requirements for the lower phases will generally be needed for the higher phases. For example, the requirements for phase two, such as the standardisation of communication protocols, are also needed for phase four.
- The measures are not exclusive to their phases, meaning that policy makers can deploy measures from higher phases even if they are in a lower phase. For example, they can deploy advanced metering and communications infrastructure (a phase three measure) even before they observe a significant impact of EVs on their operations (still in phase one). This is possible as other connected resources, such as distributed generation and behind-the-meter storage, could be taking advantage of such technology deployment.

Framework for grid integration of electric vehicles

	PHASE 1: No noticeable impact No significant impact yet. Encourage higher EV uptake through incentives and public EVSE deployment.	**PHASE 2: Flexible EV load noticeable with low flexibility demand** Distinct variability observed caused by EV charging but demand for flexibility is low enough that simple flexibility measures would suffice.	**PHASE 3: Flexible EV load is significant with high flexibility demand** Demand for flexibility is high, matching the availability of flexible EV load and paving the way for aggregated smart charging.	**PHASE 4: Flexible EV load is highly available with high flexibility demand** High flexibility demand along with highly available flexible EV load can provide energy back to the system in periods of deficit.
Charging strategy	Co-ordinate charging station deployment in areas beneficial to the grid	Passive measures: time-of-use tariffs, vehicle-based charging time delays	Deploy active measures: unidirectional V1G	Deploy active measures, bidirectional charging: V2G
Technology requirements		Hourly metering or sub-hourly metering Separate metering for EVs or onboard charging measurement devices	Real-time advanced metering and communications infrastructure	Battery state-of-health measurements
System operations	EV-EVSE interface standardisation and interoperability measures Database for EV registrations and charging points Data collection of travel and charging patterns	Enable data exchange platforms for grid operators, EMSPs, OEMs, CPOs and EV users EV-EVSE-grid standardisation of communication protocols	Forecasting of EV availability, electricity prices, VRE generation and grid constraints	Enable platforms for decentralised power trading Battery state-of-health considerations for V2G cycling Bidirectional protocols: ISO-15118-20:2022, CHAdeMO
Regulation and market design	Frameworks to incentivise demand response	Time-of-use or critical peak tariffs Self-consumption policies	Grid code definition for V1G Real-time tariffs Contracts and markets for flexibility Market access for aggregators	Reducing or eliminating two-way taxation for storage Grid code definition for V2G

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4. Improve planning practices

4.1 Conduct proactive grid planning

The typical process where grid operators respond to connection requests, in this case from EVSEs, can delay the rapid uptake of EVs. In some cases, connection requests can take from 6 months to over a year. Policy makers can streamline the interconnection process to help accelerate this process.

As the number of EVs increases, the grid will eventually need to be reinforced and expanded. Reinforcing the grid to accommodate new load can take years for permitting and construction and can thereby slow down the electrification process. Additional new charging points can utilise the existing network. In many cases, however, fast-charging stations may require a new grid connection and grid reinforcement where the existing network capacity is constrained. The connection process from request to construction approval can be a lengthy procedure. Hence, proactively planning the grid can help anticipate the connection requests.

Streamline interconnection processes

One way to streamline the process is to **mandate time windows to respond to connection requests**. For example, in the Netherlands, network operators are required to respond to connection requests within 18 weeks for capacities less than 10 MVA. Standardising interconnection procedures and publishing them can help inform the project planning and delivery of charging infrastructure.

Another tool can be to **mandate the publication of hosting capacity maps**. Hosting capacity analyses help provide grid transparency and align transport planning. The analyses are not exclusive to EV charging but can also be done for other distributed energy resources, such as rooftop PV.

Support capacity building for distribution companies

Modelling the uptake of distributed energy resources requires planners to be more sophisticated as penetration levels increase. Typical top-down planning approaches, such as econometric models or Bass diffusion models, may be simple to execute and useful at larger scales, but they may fail to account for outliers and exceptions in the distribution system areas. Meanwhile, bottom-up approaches, such as activity-based or agent-based modelling, can reflect details down to EV adoption at the household level but are computationally intensive.

California approaches this modelling challenge by mixing top-down models with higher spatial precision as a compromise, whereas the Netherlands forecasts EV adoption at the neighbourhood level and updates it every 2 years.

Common challenges include a lack of capacity of the utility staff or a lack of resources to focus on planning and modelling. These challenges have been identified in the United States but are common around the world.

Increasing the regulated revenue linked to improving the modelling and analytical capabilities of the distribution companies can help address this situation. The additional budget can allow the companies to recruit or train staff to develop the required capabilities. It can also provide them with the resources to collaborate with mobility planners who may already have modelling expertise.[13]

Provide targets and regulatory incentives for achieving electric mobility

Government targets on EV adoption can help form the basis of planning by distribution and transmission companies and consequently aid regulatory decisions. In France, for example, the Mobility Orientation Law (Loi d'orientation des mobilités) provides distribution companies with the ability to conduct medium-term planning on EV charging based on the government's targets for vehicle electrification.

Moreover, providing incentives or setting performance benchmarks tied to electric mobility and the overall energy transition can also be an option. Distribution companies in the United States identified that a lack of performance incentives for measuring support for transport electrification is one of the main barriers to proactive planning. Providing incentives through regulatory design or setting performance benchmarks based on the speed of connection of distributed energy resources can help forge proactive planning.

4.2 Reflect the full value of EV charging

Power sector planning is the process by which a selected entity, usually the system operator, outlines feasible options to meet the future long-term needs for electricity while working towards stated policy goals for climate and energy.

Long-term plans may fail to account for new technologies and their flexible capabilities, thereby leading to additional infrastructure costs. For example, modelling shows that 15% EV penetration in 2030 in a representative utility area could require transmission and distribution investments of EUR 5 800 per EV. These investments could be reduced to EUR 1 700 per EV if smart charging were considered. In Germany, the smart charging of 30 million EVs could reduce cumulative distribution network investments between 2019 and 2050 from EUR 80 billion to EUR 54 billion – a 33% reduction. Hence, reflecting the full value of EV charging can help power systems be more cost-effective.

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[13] Mobility planners may use several planning models with optimisation goals such as minimising infrastructure costs, maximising the number of EVs recharged or maximising charger utilisation. More advanced models, like POLARIS in the United States, combine activity-based modelling, which can cover EV uptake, charging location and transport mode choices.

Revisit planning criteria for grid expansions

Traditional grid expansion planning involves forecasts of the peak load and the subsequent build-up of lines, transformers and substations to provide the capacity to match that peak load. Investing instead in other alternatives, such as energy efficiency measures and demand-side flexibility programmes, to substitute for physical capacity can sometimes be more cost-effective. Case studies in the United States have shown that an average load reduction of 1-85 MW through a mixture of energy efficiency, demand response and storage can bring an average benefit-to-cost ratio of 1.40. In New York and California, these alternatives are commonly used and are known as non-wire alternatives (NWAs). Including these alternatives in grid expansion studies can help unlock the funds needed for managed charging programmes for activating the flexibility of EVs.

Applying robust cost-benefit analyses to assess these alternatives is important. Consideration of the wider aspects, such as the environmental costs of traditional upgrades (e.g., new lines and transformer upgrades), can help increase robustness. Integrating these considerations into the planning processes can help improve the business case for NWAs. For example in California, utilities must file Distribution Deferral Opportunity Reports as proof that alternatives were considered to avoid or defer upgrades or expansions.

However, policy makers must carefully balance this planning criterion with incentivising EV uptake. Focusing heavily on cost-efficient grid investment can reduce the incentives for network upgrades and delay the connection of charging infrastructure and other electrified loads.

Revisit planning criteria for system planning

Traditional system planning tends to be deterministic, where assumptions of peak load growth are projected, and generation based on conventional technologies is planned accordingly. This can lead to inefficient and expensive systems. For example, newly installed generation capacity may end up being unused if EVs and other distributed energy resources are deployed to avoid the peak load.

Large-scale electric mobility and energy transition require innovation in power system planning. Undertaking more sophisticated and probabilistic planning practices can help take into account uncertainties in generation and load and allows the participation of different technologies beyond conventional generation technologies. Probabilistic assessments on resource adequacy, as carried out in the European Union, can focus on supply security characteristics, such as the capacity value ratio (CVR).[14] They can allow more structured participation of EV flexibility, thereby informing the planning process and reducing the total system cost where applicable. For example, in the Netherlands, load shifting from EVs

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[14] The CVR is a way of assessing the value of technologies in ensuring supply security by taking the value of their contribution adapted to their availability. The ratio can be based on loss-of-load probabilities (LOLPs) and is similar to concepts such as the effective load-carrying capability (ELCC) commonly used in the United States, de-rated capacity and capacity credit.

could provide a CVR of 78.5%, meaning that a substantial part of the required capacity during peak load hours could be satisfied by EV load shifting.

Aside from changing the planning criteria, it is also important that the resource adequacy mechanisms are adapted accordingly so that the expected flexibility from EVs will actually be implemented.

Revisit regulatory design

The restructuring of incentives around revenues on capital investment is needed to reduce bias on capital expenditure. Traditional cost-of-service regulation remunerates grid companies based on the total costs they incur to deliver energy to users. This could be modified to consider revenue caps or total system expenditure (i.e., TOTEX regulation), or to consider explicit incentives for innovation, such as supporting EV smart charging.

For example, in the United Kingdom, the Revenue Using Incentives to Deliver Innovation and Outputs (RIIO) regulatory framework combines the total system expenditure approach with performance and innovation incentives, rewarding companies that invest in innovation and meet the needs of consumers and network users. Such measures are effective in helping distribution network operators to proactively pilot smart-charging trials based on regulator-approved incentives.

Co-operation of transmission and distribution companies

A common difference between vertically integrated power sectors and unbundled ones is the separation of the distribution system from transmission system operations. The transmission system traditionally facilitates electricity delivery from connected generators to separate distribution systems.

With the higher participation of demand flexibility and increasing amounts of distributed energy resources, distribution systems are becoming more prominent as they can affect operations at the transmission scale. In addition, actions in one domain may not always align with the operational objectives of another. For example, aggregated smart-charging participation in transmission-level frequency regulation can affect the local distribution grid’s voltage regulation objectives.

However, this also highlights the need for co-operation to solve common problems. For example, higher shares of variable renewable generation could result in changes in the power flow at the transmission level due to changes in generation output. In such cases, co-ordination with different demand areas in distribution networks could help in balancing and maintaining system stability.

Annex

Charging modes and levels

Charging modes are based on the manner of connection of EVs to the power grid. Modes 3 and 4 have embedded communication and control capabilities that can start and stop charging and modulate charging power when needed.

Charging modes based on IEC 61851-1

Mode	Description	Application
Mode 1	Direct connection to a regular domestic socket	Typically used for electric micro-mobility options and two- and three-wheelers. Prohibited in the United States due to the risks involved.
Mode 2	Direct connection to a regular domestic socket with residual current device protection	Typically used for two- and three-wheelers and light-duty vehicles via a portable charger containing residual current device protection. Prohibited from public areas in Italy; restricted in the United States, Canada, Switzerland, Denmark, France and Norway.
Mode 3	Dedicated EVSE connection with security and communication capabilities	Can exist in a wallbox format that can be installed in residential areas. Commonly constructed in public AC charging.
Mode 4	Dedicated EVSE connection with AC-DC conversion and security and communication capabilities	Used for DC fast charging for a wide variety of power levels.

Sources: IEC (2017), IEC 61851-1:2017 Electric Vehicle Conductive Charging System - General Requirements; IEC (2014), IEC 61851-24:2014 Electric Vehicle Conductive Charging System - Digital Communication Between a D.C. EV Charging Station and an Electric Vehicle for Control of D.C. Charging; Schneider Electric (2021), Electric Vehicle and EV Charging Fundamentals.

Charging levels, on the other hand, are classified based on the power level as a combination of the current and voltage that the connection can handle. Due to differences in voltages and typical amperage limits among countries, the actual charging power can vary. For example, most countries in Europe have regular sockets rated 230 V and 16 A, which can theoretically provide 3.7 kW, whereas in India they are rated 230 V and 15 A, resulting in only 3.3 kW.

The typical labels of “trickle”, “slow” and “fast” charging are based on the speed of level 1, 2 and 3 charging in relation to light-duty vehicles. However, the charging speed actually varies based on the vehicle type, such that a two-wheeler can “fast charge” with a level 2 charger, and a bus can “slow charge” with a level 3 charger.

Charging levels based on various power levels

Level	Description	Application
Level 1	1.9 kW AC (single-phase 120 V, 16 A)	• Common in North America due to the 120 V mains • Technically absent in countries with 220 V mains • Charging of two- and three-wheelers and light-duty vehicles
Level 2	3.5-7.7 kW AC (single-phase 220 V and 16 A, to 240V and 32 A) 11-22 kW AC (three-phase 400 V and 16 A, to 400V and 32 A) 15 kW DC (India)	• Common in Europe, Asia (except Japan), Africa and South America (except Colombia, Venezuela and Ecuador) with a mains voltage of 220-240 V • In North America, 240 V sockets may be provided, especially for clothes dryers and stoves • In India's Bharat AC 001 standard, a three-phase input with three charging points of 3.3 kW each; lower-power DC charging also available through Bharat DC 001 • Charging of two- and three-wheelers, light-duty vehicles, and smaller buses and light commercial vehicles/trucks
Level 3	50-350 kW DC	For fast charging of light-duty vehicles and slow charging of bigger buses and trucks
Level 4	350 kW to 3.75 MW DC	For fast charging of buses and trucks

Sources: IEC (n.d), World Plugs (accessed 27 October 2022); Schneider Electric (2021), Electric Vehicle and EV Charging Fundamentals; ENTSO-E (2021), Electric Vehicle Integration into Power Grids; CharIN (2022), Megawatt Charging System (MCS).

Alternative charging techniques

- **Inductive charging**. Similar to wireless charging for cell phones, the batteries in EVs can be charged using magnetic resonance through a transmitter pad connected to the grid. While inductive charging is still nascent, standards have already been developed. The model has the potential for being integrated into roads and parking lots, providing virtually unlimited range and enabling the use of smaller batteries.
- **Catenary wiring**. Similar to trains or tramways, vehicles with defined routes, such as buses and trucks, can be connected directly to the grid through catenary wiring. Urban electric trolleybuses connected by catenary wiring are already common in certain cities. Life cycle cost assessments have shown that sectional catenary trucks with a 120 kWh capacity are more cost-effective compared to battery electric trucks with an 825 kWh capacity at EUR 0.68 per km to EUR 0.72 per km, respectively, for the same tonnage.
- **Mobile EV charging**. Battery piles that are mobile or piles carried by vans can provide charging solutions for EVs while the battery piles themselves are charged in a dedicated location. By being mobile, they can be charged where there is grid capacity, saving on land acquisition and installation costs and reducing the need for multiple fixed EVSE stations. This can sometimes be a temporary solution before the installation of a fixed EVSE. Studies on the levelised cost of electricity in China show that mobile charging is cost-competitive with fixed EVSE if the utilisation rates of the latter are lower than 39% and if land acquisition is not subsidised. Fixed EVSE will still be needed though, despite the expansion of mobile EV charging. Some companies in the

United States and the United Kingdom cater to charging provisions under land or grid capacity constraints and rescue use cases when a vehicle is stranded. Mobile EV charging is sensitive to battery costs, but it has the flexibility to use lower energy density batteries or second-life batteries, thereby improving the utilisation of extracted battery materials.

- **Automated conductive charging**. Innovations in EV-EVSE charging interfaces are still ongoing, with the aim of improving user convenience. Innovations in automated conductive charging aim to lower infrastructure costs and help the scalability and ubiquity of charging infrastructure. Several demonstrations are ongoing in Austria and offer bidirectional charging capabilities.

Abbreviations and acronyms

AC	alternating current
CPO	charge point operator
CVR	capacity value ratio
DC	direct current
ELCC	effective load-carrying capability
EMSP	electric mobility service provider
EV	electric vehicle
EVSE	electric vehicle supply equipment
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LOLP	loss-of-load probability
NWA	non-wire alternative
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
OpenADR	Open Automated Demand Response
OSCP	Open Smart Charging Protocol
PPA	power purchase agreement
PV	photovoltaic
ToD	time of day
ToU	time of use
VRE	variable renewable energy

Glossary

CO_2-eq	carbon dioxide equivalent
GW	gigawatt
kW	kilowatt
kWh	kilowatt hour
TWh	terawatt hour

For further information, please contact: Renewables Integration and Secure Electricity Unit (EMS-RISE@iea.org).

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Typeset in France by IEA - December 2022
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