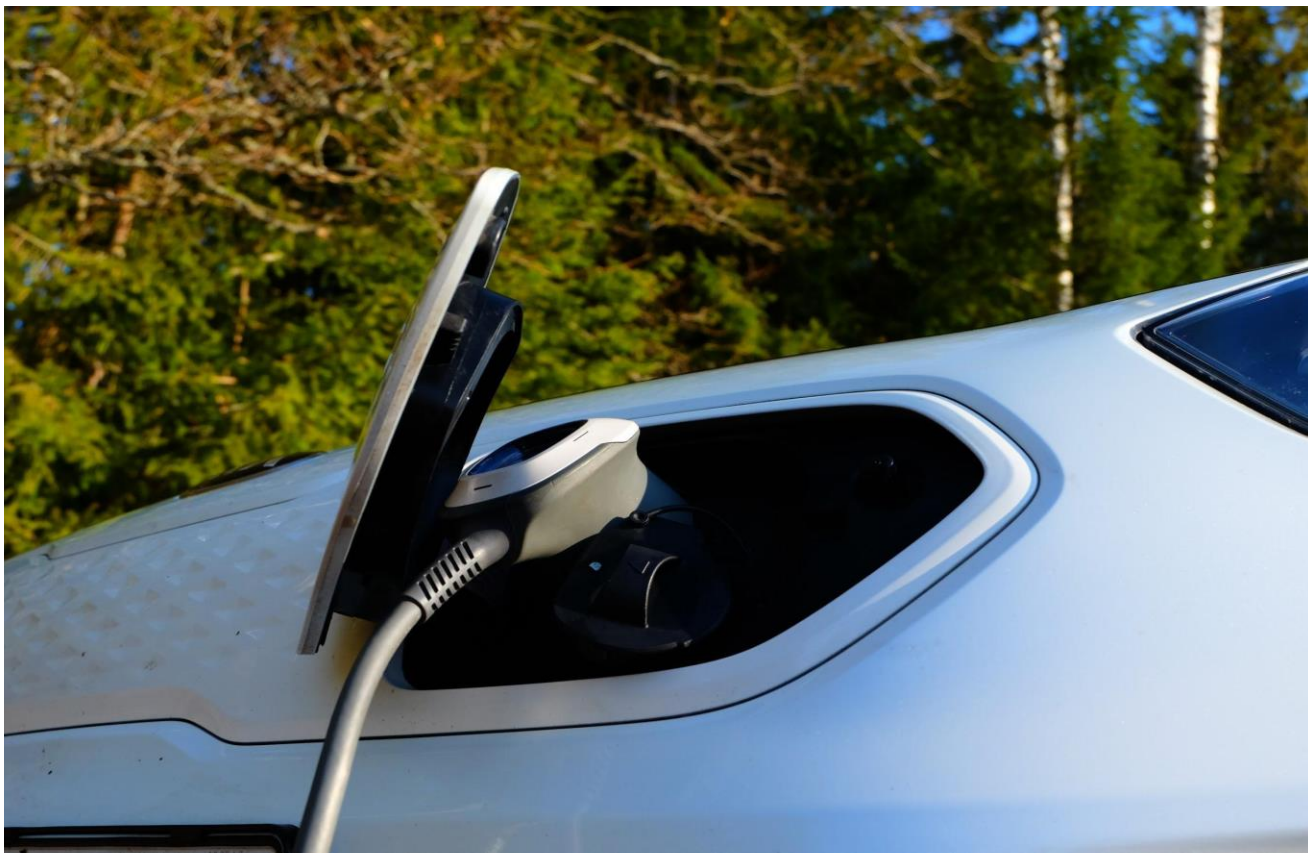
Electric Vehicle and Power System Integration: Key insights and policy messages from four CEM workstreams



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Key policy messages on electric vehicle–power system integration

The Clean Energy Ministerial (CEM) recently organised an initiative to facilitate cross-sector collaboration between stakeholders from the power and transport sectors. Its aim is to address concerns at the intersection of electric vehicles (EVs) and the power grids on which they depend for charging. With the number of EVs growing rapidly, pressing questions have emerged on how to integrate them efficiently into the electricity system and ease related challenges. Related topics include the best way to develop and enable solutions that support vehicle electrification and a range of new flexibility opportunities.

This report summarises the opportunities to couple the road transport and power system sectors. It articulates policy messages based on current experience, with a particular focus on the role of critical stakeholders in a transformation that crosses multiple sectors. Many of these findings emerged from a highly interactive virtual workshop held on 19-20 April 2020, which engaged approximately 75 international experts from 18 countries and diverse backgrounds. In addition to the workshop, the participants also contributed by completing a questionnaire and interacting on a web platform created in advance specifically for the workshop. The report also integrates insights from the individual participating CEM workstreams, for example, the Global Electric Vehicle Outlook 2020 report from the CEM EVI (IEA, 2020a).

Here is a summary of the initiative's main policy findings, with a more complete discussion of each later in the report.

1. **Vehicle electrification is a critical building block in the ongoing energy transition towards a more sustainable and resilient future.** Co-ordinated action can produce beneficial synergies with electrification in other sectors and power system transformation.
2. **Maximising the benefits of transport electrification requires the active engagement of stakeholders at many levels** – across government ministries, through public–private co-operation, with international standards that ensure interoperability, and by effective system integration and sector coupling.
3. **Mechanisms to integrate EVs and the power system need to be designed with regard to EV users and their mobility needs as well as the optimal use of grid assets.** Understanding the diversity of mobility needs is essential to designing load management and demand response programmes that are convenient, attractive and rewarding for EV users, and enable their full participation in electricity markets.
4. **Infrastructure planning is central to supporting vehicle electrification.** This includes deploying an ecosystem of cost-effective and convenient public and private chargers, and considering EVs in power systems and in mobility planning.
5. **Enabling the successful integration of EVs into the power system at both grid-wide and local levels will require a diverse array of technological solutions, closer collaboration among stakeholders, and potentially changes to regulations and market design.**

Introduction and project background

Plug-in EV adoption (including two- and three-wheelers, cars, vans, trucks, and buses) is growing rapidly in many parts of the world, driven by policies to reduce transport emissions and the rapid reduction of battery costs. EV charging is resulting in new electricity demand, introducing both integration challenges and opportunities for electric power systems. At the same time, the power system is also evolving rapidly. On the supply side it has to accommodate growing shares of variable renewable energy (VRE) generation and distributed resources like energy storage and rooftop photovoltaic (PV). On the demand side it is experiencing more electrified load and more active customer participation in electricity markets.

These changes open up opportunities to take advantage of EV flexibility and optimise the integration of transport and power systems to benefit customers and support decarbonisation across sectors. As a result, policy makers are faced with the challenge of optimising electricity systems that are in evolution while supporting the deployment of EVs and renewable energy. This challenge translates into a set of questions and opportunities: How to enable sustainable, reliable and affordable mobility solutions, including vehicle electrification? How to reap the benefits associated with these new assets? How to optimise infrastructure investment and operational decisions to promote the efficient functioning of the future electricity and transport systems? How to provide energy resilience and security amid growing demand while integrating larger shares of EVs and VRE?

The acceleration of digitalisation and automation is changing the way that our transport and power systems function. With new technologies and better interconnections, there are opportunities for new business models (e.g. ride-hailing and the sharing economy) and to better integrate electricity demand and supply. As the electrification of transport and decarbonisation of electricity systems progress, the critical task for policy makers is to create a suitable policy and market framework. This means a framework that enables reliable, secure and resilient electricity and transport systems at the lowest possible cost, while ensuring sustained revenue streams to owners of central and distributed assets. Achieving fully integrated mobility and power systems requires unprecedented co-ordination between charging infrastructure, the power system as a whole and EVs, including rewards for demand-side flexibility. Looking at each of these components in isolation may lead to missed opportunities.

This report summarises lessons learned in a recent CEM collaboration on the nexus between EVs and power systems. The project saw four workstreams join forces: the International Smart Grid Action Network (ISGAN), the 21st Century Power Partnership (21CPP), the Electric Vehicles Initiative (EVI) and the Power System Flexibility (PSF) campaign. This initiative amplified ongoing work at the intersection of the two domains across the four workstreams. It focused on easing the integration of a rapidly growing number of EVs and their interaction with the electricity system. This enabled the policy implications to be articulated based on current experience, with particular focus on the key stakeholders and their potential roles in this multi-sector transformation.

Vehicle electrification is a key building block in the transition towards a more sustainable and resilient energy future.

Driven by environmental policies and technological progress, the world's energy system is rapidly changing. VRE technologies and battery storage are increasingly becoming cost-competitive and are reshaping electricity generation and energy use. The acceleration of digitalisation and automation is changing the operation of our power and transport systems. This enables decentralised generation and active user participation in electricity markets, and the emergence of on-demand ride-hailing for transport, creating new business models. Opportunities have become available to fully integrate electricity demand and supply, with new and better technologies and options for interconnection and communication.

The result is that energy systems of the future can be optimised to benefit customers and support decarbonisation across sectors. And the adverse impacts of transport on health, the climate and the environment can be alleviated with vehicle electrification, now within reach thanks to low-cost clean electricity and energy storage technologies.

Accounting for approximately a quarter of global energy sector GHG emissions (IEA, 2020b), the transport sector is a priority for decarbonisation. In 2019 there were about 8 million EVs in circulation in the world (including 7.2 million passenger cars, and 0.8 million light-commercial vehicles, buses and trucks) (IEA, 2020a). At least 140 million EVs are expected by 2030 under a scenario considering existing and announced policy measures (the IEA Stated Policies Scenario), and 245 million under the IEA Sustainable Development Scenario (IEA, 2020a). This could result in emission reductions of two-thirds relative to an equivalent fleet of conventional vehicles (or 450 Mt CO_2-eq). However, it also means that global demand for electricity would increase by nearly 1 000 TWh in 2030 under the Sustainable Development Scenario, representing 3-6% of total final electricity consumption in many countries and around 4% globally (IEA, 2020a).

Transport electrification is only one aspect of the broader transformation that will be needed across the energy system to realise the IEA Sustainable Development Scenario. It also includes a major increase in electricity demand for space conditioning, especially in emerging economies, and large shifts in electricity supply towards cleaner resources. The IEA estimates that by 2030 VRE can account for as much as three-quarters of the additional capacity needed to meet increasing electricity demand, in particular for transport, heating and cooling (IEA, 2020c).

By 2030 electric light-duty passenger vehicles are expected to dominate electricity demand for transport, but larger commercial vehicles are likely to constitute a notable share of charging demand. In 2030 under both IEA scenarios, China, Europe, the United States, Japan and India will account for most EV sales, but between one-quarter and one-third will be in a variety of other countries and regions. Electric powertrains are three to five times more energy efficient than conventional internal combustion engine vehicles, providing unmatched potential for energy efficiency improvement in road transport. Electricity demand for EV charging is expected to reach 1-6% of total electricity demand in leading regions, and the majority of charging demand is expected to come from residential charging of light-duty vehicles. This could add stress to residential distribution systems, but also opens up significant opportunities for smart charging, for example postponement of residential charging to off-peak hours, while fully meeting all the EV owners' mobility requirements (IEA, 2020a).

Policy plays a critical role in mobility and EV market development, spanning incentives, regulatory measures and support for vehicle owners/operators, as well as initiatives to support alternative transport modes, education and customer awareness. Behavioural change is also a critical part of the holistic approach to sustainable mobility – it includes avoiding unnecessary trips and shifting car ridership to public transport, ride sharing, cycling and walking. Increased digital working (teleworking, digital meetings) and rethinking the allocation of urban space can encourage this change. In addition, associated land-use planning for transport and charging systems needs to be considered. EV adoption and use projections must account for these mobility changes to properly plan for power system integration.

Key findings:

- Vehicle electrification is a critical component of broader electrification trends and energy system transformation. Opportunities exist to integrate and optimise the energy systems of the future to benefit users and support decarbonisation across sectors, for example through smart EV charging and grid-integrated planning.
- Transport accounts for approximately a quarter of energy sector GHG emissions and is a priority sector for decarbonisation and the reduction of harmful pollutant emissions; in this context, EVs have significant environmental merits.
- Clean transport solutions must consider new mobility options and account for behavioural changes when planning for future urban design and power systems.

Maximising the benefits of transport electrification requires the active engagement of stakeholders at multiple levels to ensure interoperability, effective system integration and sector coupling.

Governments need to champion a multi-stakeholder approach in their jurisdictions so that electricity-based mobility (eMobility) solutions and power system transformation can co-evolve efficiently. They should also support international dialogue and co-ordination. In the particular case of EVs, the potential benefits will span multiple ministries and industries, relating to lower energy expenditure, reductions in emissions, optimal utilisation (e.g. VRE integration) and improvements in the efficiency of the power system, security of supply and investment in infrastructure. A wide range of stakeholders will need to be involved, including regulators and policy makers, road vehicle manufacturers, charging providers, power sector companies, building developers, municipalities and final users. Cross-border dialogue also needs to be established at global, national, regional and local levels.

EV–power system integration requires a cross-sectoral discussion and a holistic approach (i.e. embracing the power, transport and urban planning sectors). The workshop held on 19-20 April 2020 was a first attempt to bring representatives of these multiple sectors together to develop a comprehensive viewpoint on EV–power system integration within broader electrification trends. In this context, infrastructure planning is a critical component to support vehicle electrification. It includes:

- Planning and support for adequate deployment of private charging infrastructure (currently representing the bulk of EV charging demand).
- Proper design of an ecosystem of cost-effective and convenient public charging networks.
- Planning for distribution systems considering EV loads.
- Integration with urban mobility planning.

Cross-sector co-ordination between government ministries and agencies breaks through traditional mandates and processes to enable sector coupling. Beyond this, it is important to engage regulators, technology providers and investors so that, by ensuring new system resources meet the necessary capabilities, these stakeholders validate them in their long-term plans and regulatory standards.

Figure 1 – Breaking the silos of policy making

	Transport and infrastructure stakeholders		Energy and power sector stakeholders	
Overarching policies	EV uptake targets Transport sector emission reductions Energy efficiency targets	↔	VRE penetration targets End-use electrification targets Energy efficiency targets	Overarching policies
Country-wide infrastructure	Charging infrastructure roll-out programmes Accepted charging standards Roaming and long-haul travel arrangements	↔	Need to reduce peak-demand increase Balancing VRE Rising transmission costs	Bulk power system and transmission network
Mobility, land-use and urban planning	Charging depot requirements Local mobility blueprints	↔	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, storage, etc.

International standards that ensure the interoperability and reliability of technology are critical for accelerated uptake of EVs.

A typical aspect in the introduction of any new technology is the link between end users and critical infrastructure. Convenient and cost-effective private and public charging is critical to enabling and supporting widespread EV adoption. It is being addressed by governments, technology providers and vehicle manufacturers. However, without appropriate interoperability platforms and roaming agreements something as simple as charging at a station in another district or in a neighbouring country can become very problematic. EV charging service providers can learn from other industries (e.g. telecommunications and banking) to offer a seamless service to nationally and internationally mobile customers. Policy makers also have a role here. They can facilitate and accelerate this process, for example by supporting investment in infrastructure that might not be profitable in the early EV adoption phase, or by supporting and enabling EV participation in electricity markets. They can also protect users from unjustifiably high service charges.

Behind the customer-facing experience, data exchange platforms and visibility mechanisms need to be established so that power system operators and EV charging networks can account for charging patterns in their day-to-day operations and eventually in network expansion plans. Lastly, policy makers and regulators need to collaborate with manufacturers and user groups to ensure that all grid-connected devices are secure. They need to be secure both in terms of data privacy and also free of vulnerabilities that could expose the power system to malicious cyber-attacks. There is a growing body of literature looking at how attackers strategically target assets to disrupt power supplies by combining knowledge of factory settings in connected devices and grid information.

Key findings:

- A multi-stakeholder process is needed for the co-evolution of vehicle electrification and power system transformation. In the particular case of EVs, benefits from lower energy expenditure, reductions in emissions, VRE integration and investment in infrastructure will span across ministries and industries.
- EV–power system integration requires a cross-sectoral discussion and a holistic approach (i.e. across the power, transport and urban planning sectors). In this context, infrastructure planning is an essential component to support vehicle electrification: it includes planning distribution systems to reflect EV loads, properly designing and deploying convenient and cost-effective public and private charging solutions, and integration with urban mobility planning.
- To promote the adoption of EVs, infrastructure providers need to collaborate with the relevant authorities (e.g. city and transport authorities) to ensure that users are provided with relevant and high-quality information about charging options and associated costs. This is integral to users feeling confident in using the technology.
- Open protocols and international standards are needed to ensure the compatibility of charging infrastructure and EVs. This is especially important for linked markets (e.g. Europe and North Africa, the United States and Canada).

EV–power system integration mechanisms need to be designed around EV users and their mobility needs, as well as the optimal use of grid assets.

The first step to successfully integrating transport and power systems is to understand the diversity of mobility needs and modes, electrification solutions and electricity loads associated with EV charging (Muratori et al., 2020). The typical conversation on transport electrification centres on personally owned passenger cars, but there is growing interest in commercial vehicles. EV adoption is also moving from early adopters to mainstream markets (IEA, 2020a). Electric two- and three-wheelers, cars, vans and buses are penetrating more market segments and regions, while medium- and heavy-duty electric trucks are also emerging. Many expect EVs soon to become cost-competitive with diesel trucks for heavy-duty road transport in some regions (Phadke et al., 2019). Vehicle fleets, whether light-duty (e.g. ride-hailing), commercial (e.g. delivery trucks) or bus fleets, are promising candidates for vehicle electrification, given the lower operating costs compared to conventional vehicles and the great emission reduction potential (Jenn, 2020). Given their operating patterns and charging requirements, these vehicles could integrate with and support the power system in different ways.

EV–power system integration mechanisms need to be designed in a way that is convenient, attractive and rewarding for EV users and at the same time efficient for the power sector. This highlights the central role of users in EV integration. Satisfying mobility demand will remain the primary purpose of EVs. However, optimising the impact of their electricity demand on power systems via smart charging programmes can support EV adoption and has shown high user acceptance (Hildermeier et al., 2019). Moreover, impacts on vehicle batteries need to be taken into account. Further opportunities may arise to optimise power system integration, reap synergies with VRE and reduce electricity costs for all users, but this potential needs to be assessed reasonably given that it will be secondary to mobility needs.

Policy makers should bear in mind that policies and solutions that target demand-side measures, such as co-ordinated EV charging, also enable other demand-side distributed resources to participate in the market. These include:

- Off-peak charging: historically offered by some utilities for heating loads, load postponement via differentiated electricity tariffs is already in use and can also be leveraged to reshape EV charging. Increased digitalisation enables control over more devices, with greater temporal and locational granularity to better match the variability of renewables.
- Aggregation of small resources connected at local networks: being able to manage and control flexible distributed resources, such as a fleet of EVs, is key to providing services both at system and local levels.
- Local flexibility markets: activation of flexibility from distributed resources allows investment in traditional distribution network assets to be avoided or altered and improves the integration of VRE.
- Direct renewable charging: co-placement of distributed renewable generation with charging infrastructure (e.g. rooftop PV at home and high-power charging stations) is attractive to users and can provide synergistic benefits. Under certain circumstances, it can be cost-effective and also reduce infrastructure needs and stress on grids.

- Flexible loads and behind-the-meter storage: incorporating smart control of flexible loads and distributed energy storage can support system planning and operation and reduce overall costs.

Charging during system peak hours can be largely alleviated with simple solutions implemented via relatively straightforward forms of policy support. For example, promoting workplace charging in systems with high PV penetration or implementing dynamic and local time-of-use electricity tariffs can be effective. Time-varying tariffs to support EV smart charging, from the simple to the more granular, are widely available. They are helped by the roll-out of smart meters and have proved an effective tool. This should include EV charging tariffs in the future. Table 5.2 of the Global EV Outlook 2020 shows an overview of existing EV flexibility programmes (IEA, 2020a). However, regulatory and market frameworks would have to be adapted to unlock the full flexibility potential of EVs. It would enable the system operator to optimally vary the time or power level at which an EV is charged (smart charging) or allow the EV to inject electricity into the home/building/grid (vehicle-to-grid services, V2X). This way the system would reap synergies with VRE generation and reduce electricity costs.

Policy makers should consider two issues. First, simple market mechanisms such as time-of-use rates need to be properly designed to avoid unintended consequences, such as rebound peaks in electricity load (Muratori and Rizzoni, 2016). Tariffs should be designed to offer a broader range of time-varying or dynamic rates that incentivise effective smart charging. Second, business models and regulatory changes may be required to balance bulk power system and distribution system benefits. Distribution network operators should be allowed to take a more active role in electricity markets. Policy can enable this by providing a neutral platform for operators to tap into the inherent flexibility that EVs (and other flexible resources) offer.

Specific stakeholders such as aggregators are also needed for EV batteries to contribute to supporting the power system on a meaningful scale (IEA, 2020a). They will also handle on behalf of EV users the complexity of monetising their flexibility on markets. Finally, business models are needed that make use of new regulatory frameworks to reward owners of EVs (and other flexible resources) for providing flexibility services, together with easy and accessible demand response programmes. They should be designed to encourage sustained participation.

Key findings:

- It is essential to understand the diversity of mobility needs and modes and different electrification solutions so that policy makers can prioritise the right policy programmes and support vehicle electrification.
- EV charging solutions offer opportunities to optimise their integration into the power system, but this potential needs to be assessed reasonably given that flexibility will be secondary to mobility needs.
- Effective incentives need to be designed and implemented to compensate users for providing flexibility. Regulators can facilitate this by redesigning tariffs and cost-recovery mechanisms, enabling electricity providers or aggregators to simplify the active participation of final users. This can be either through explicit schemes with direct remote control, or implicit programmes where participation is encouraged through price signals.

Infrastructure planning is central to vehicle electrification, calling for an ecosystem of cost-effective and convenient public and private chargers and considering EVs in power system and mobility planning.

Different EV and charging infrastructure technologies can be deployed to meet increasingly diversified needs. However, convenient and cost-effective charging infrastructure to meet public and private charging demand is a fundamental prerequisite for the effective roll-out of EVs. Home charging, whether in individual homes or multi-dwelling buildings, workplace charging and public charging are all essential. High-power (i.e. rapid) and strategically sited public charging is also needed to support EV adoption by users who cannot rely on private chargers and to enable long-distance travel for passenger EVs and some commercial applications (Wood et al., 2017). Charging infrastructure, of course, needs to be carefully assessed using mobility and grid planning to best serve the needs of EV drivers, while also including consideration of user behaviour and new mobility options: public transport, cycling and walking, car-sharing and ride-hailing services. The associated land-use planning for transport and charging systems equally needs to be considered.

Integrating EVs into the power system offers an opportunity to upgrade legacy systems, increase resilience and, as discussed later, support VRE integration and reduce electricity costs for all users. The cost of electricity can be reduced both for EV owners and other users by designing effective market and charging infrastructure and fully integrating the power system.

Different charging solutions and strategies are available:

- Uncoordinated charging, in which each EV is charged without any consideration for the grid or price of electricity.
- Off-peak charging, where the EV user picks specific time slots for charging based on awareness of grid congestion and/or lower electricity price times, within the constraints of the EV user's mobility needs.
- Co-ordinated or "smart" charging (unidirectional), which involves optimally varying the time or power level at which an EV is charged based on dynamic signals from the electricity provider.
- Vehicle-to-grid services (V2X or V2G), which enables bidirectional power flow between EVs and the grid or other systems so that EVs become electricity suppliers

These different technologies yield different combinations for reshaping electricity loads, managing the network locally, reducing the overall system peak and providing support to the power system. They gradually unlock greater potential benefits for power systems (starting with off-peak charging all the way to V2G). However, they also have different implications for electricity market design, business models, infrastructure needs and policy and regulatory changes. Different strategies for rolling out infrastructure for charging, electricity distribution and metering affect the charging options available to users, and also their impact on and ability to engage with the grid. For example, residential charging enables use of night-time wind generation and workplace charging aligns with middle-of-the-day solar generation.

Key findings:

- Expanding the charging network is a fundamental requirement for effective EV roll-out – it is essential to enable home charging as well as workplace and publicly accessible charging.
- Well-designed charging infrastructure and power system integration can support decarbonisation and lower costs, both for EV owners and electricity users in general.
- Different pathways for rolling out charging infrastructure affect the mobility options available to users and the ability to engage with the grid.

Successfully integrating EVs at the bulk power system level and the local level requires a diversity of technological solutions, closer collaboration among stakeholders and possible regulatory and market design changes.

Carefully designed electricity markets will facilitate the electrification of the transport system and can unlock opportunities for cross-sector integration. EV charging affects both aggregate power demand – and therefore requirements for bulk power system capacity (generation and transmission) – and distribution systems at the local level, which are impacted by high-power or clustered loads. Several studies show that EV charging can represent a significant increase in electricity demand, but increased EV adoption is expected to have only limited impact on the operation of bulk power systems (RTE, 2019; USDRIVE, 2019). EVs could account for 4% of global electricity demand by 2030 in the Sustainable Development Scenario (IEA, 2020a) or almost 25% of US electricity demand by 2050 in a high electrification scenario (Mai et al., 2018).

Many different factors will determine how EVs integrate with and affect existing distribution systems, including network characteristics, the capacity of existing grid assets to accommodate EV charging (Hogan, Kolokathis and Jahn, 2018), and future load changes beyond EVs. Detailed analysis is needed to assess local distribution-level impacts and enable optimal integration. At the same time, EV charging flexibility and the use of the batteries to balance a system with flexible demand and power infeed offer great opportunities to optimise power system planning and operation, reaping synergies with VRE generation. The potential exists to reduce electricity costs for all users and in particular EV owners. Extracting all the value both for EV owners and for the power system requires active engagement between policy makers and stakeholders from a range of different areas, including those responsible for retail electricity pricing, business models and regulations.

EV–power system integration: Unlocking flexible charging and the value of EVs as grid resources

Through off-peak charging, co-ordinated charging and V2G services, EVs can help reduce the need for power system capacity expansion and support the better use of the existing power system (RTE, 2019; Zhang et al., 2019). Flexible EV charging creates several opportunities to mitigate potential impacts on bulk and distribution systems, reduce electricity costs (for EV owners as well as other users), generate additional value by providing ancillary services and support the integration of VRE in the power system. Beyond reducing the need for additional generating capacity and assisting power system operation, co-ordinated charging can be used to further reduce carbon and pollutant emissions by aligning EV charging with renewable electricity generation (Hoehne and Chester, 2016). However, whatever flexibility potential might be offered is constrained by EVs' primary use – mobility – and its potential impact on the individual vehicle's lifetime through additional wear and tear. This means flexibility needs to be assessed taking all factors into account, given that flexibility will be secondary to mobility needs.

As discussed above, relatively straightforward forms of policy support can largely alleviate problems with peak-hour charging, such as promoting workplace charging and dynamic time-of-use residential tariffs. Co-ordinated charging and V2G can unlock the full flexibility potential of EVs by optimally varying the time or power level at which they are charged. Different charging options and infrastructure can encourage alignment between EV load and VRE generation.

In the IEA's Sustainable Development Scenario, making full use of EV flexibility yields a number of benefits, including:

- Shifting load to periods of high VRE output.
- Reducing system ramps.
- Reducing VRE curtailment.
- Making use of low-cost resources.
- Allowing for more stable operation of other dispatchable assets on the power system.

At periods of minimum load, smart EV charging can contribute to raising minimum load levels, and may potentially help inflexible thermal generators avoid operational constraints or negative prices when there is excess VRE generation. EVs could also act as distributed energy resources to the grid (for use by other loads such as buildings) via V2G applications. This would take advantage of the 16 000 GWh of energy storage capacity that is projected across all EVs by 2030 in the IEA Sustainable Development Scenario. In the same scenario and under the conditions of the analysis, in particular assuming that V2G technology is widely available by 2030, V2G could provide as much as 600 GW of flexible "generation" capacity at peak times across China, Europe, India and the United States (IEA, 2020a). The full implementation costs and benefits of demand response or V2G programmes will come into sharper focus as technologies mature and grid operators experiment with different tariff structures and business models.

The combination of technological and regulatory or market solutions that enable off-peak charging, co-ordinated charging or V2G can greatly contribute to integrating the entire system, limiting increases in peak loads, increasing overall alignment with VRE generation and more. One study shows that under California's 2020 renewable portfolio standard, co-ordinated EV charging could deliver the same renewables integration benefits as California's energy storage mandate, but at substantially lower cost. Bidirectional V2G services could deliver up to three times the value of controlled EV charging in some cases (Coignard et al., 2018). Another example of the importance of co-ordinating EV charging as one of many system resources can be found in a study of the flexibility requirements of China's power system in 2035. It shows a peak load reduction of 165 GW, or about 14%, thanks to smart EV charging (IEA, 2019).

EV–power system integration: Local distribution network perspective

As previously discussed, local concentrations of EV adoption can have specific impacts on the distribution system. Local electricity distribution systems (already responsible for approximately one-third of total electricity costs) are likely to take the greatest burden of EV charging, especially in areas where EV adoption might be clustered, for legacy distribution systems and where higher-power charging takes place (Muratori, 2018). In Germany, for example it is estimated that between 2018 and 2035 the total cost of distribution network reinforcements to accommodate new distributed generation and EV loads will rise to EUR 36.8 billion (E-Bridge, NODES and Pöyry, 2019). However, recent studies show that when accounting for flexibility in the use of these new resources, the total investment can be reduced by approximately 50% (Agora Verkehrswende, Agora Energiewende and RAP, 2019; E-Bridge, NODES and Pöyry, 2019).

When considering the integration of EVs into distribution networks, it will be important to take into account the current state and carrying (or hosting) capacity of the specific distribution network. In countries reliant on gas networks for heating (e.g. the United Kingdom and the Netherlands), distribution networks may not be designed for such high electricity loads locally. EVs, as new loads, could introduce local stress to existing distribution systems, even at relatively low overall adoption levels, due to load clustering ("the neighbour effect"). By contrast, in countries like France and Sweden that have designed their distribution networks to cope with electric heating loads, it might be easier to accommodate EV loads; however, local challenges may still appear in cities with rising local electricity demands and constraints on distribution network expansion. In other countries where electricity demand is rising rapidly as a result of electrification of other end uses (e.g. heating), network reinforcement plans and mobility needs will need to be looked at within an integrated planning framework.

Local impacts will vary significantly for different systems as a result of load heterogeneity, interaction with other loads and distributed VRE, and differences in legacy distribution infrastructure. Stationary energy storage can be used to mitigate impacts on distribution systems and reduce charging costs (for example, by limiting costs associated with demand charges [Muratori et al., 2019]). Equally, EV charging loads and VRE generation might take place at different locations. Cities with high concentrations of electric mobility may not have sufficient local distributed generation capacity and rural areas with high shares of VRE penetration may not have a high enough density of EV users to absorb local injection peaks. In such cases, co-ordination between the distribution and transmission levels will be important to balance load and supply across different areas (CoordiNet, 2018; Lind et al., 2019).

In addition to the measures mentioned above, there is significant potential for co-ordinated action between network operators, regulators and mobility service providers to facilitate EV integration. Electrification of public-transport, commercial-vehicle and ride-hailing fleets might also offer an opportunity to co-ordinate the planning and construction of charging depots with local network conditions. In this sense, establishing communication channels, early engagement and information sharing between such actors can significantly boost local transport electrification while minimising grid impacts.

One example is the EU Horizon 2020 CoordiNet project. It aims to demonstrate how distribution system operators (DSOs) and transmission system operations (TSOs) can act in a co-ordinated way to procure and activate system services in the most reliable and efficient way (CoordiNet, 2018). This is being done through three large-scale demonstrations in Greece, Spain and Sweden. The CoordiNet project is centred around three key objectives:

1. Demonstrate the extent to which co-ordination between TSO/DSO leads to more economic, reliable and environmentally friendly electricity supply to consumers.
2. Define and test a set of standardised products and related parameters for system services, including the reservation and activation process for the use of assets and finally the settlement process.

3. Specify and develop a TSO–DSO–consumer co-operation platform, starting with the necessary building blocks for the demonstration sites (CoordiNet, 2018).

These components should pave the way for the development of an interoperable pan-European market that allows all market participants to provide energy services and opens up new revenue streams for users providing system services.

Changes in distribution network regulation to allow smart solutions

EV charging flexibility can be leveraged to minimise local impacts, but a further limitation for the effective integration of EVs and VRE generation at the distribution level may arise from institutional barriers. Historically distribution networks were established as passive unidirectional infrastructure and distribution costs are not explicitly set out in current retail electricity prices. Consequently, regulatory changes may be required to allow DSOs to take a more active role in managing local flexibility requirements and to create a business case offering both better quality of service and lower costs to end users. Given that this is more of an institutional challenge, a longer or more complex process might be implied in enacting regulatory change across the country, or even in changing the business model of existing distribution companies.

The United Kingdom's ongoing "Charging Futures Forum" is an example of the complexity of such processes, where revisions to network charges and retail rate-setting are being driven by the regulator, Ofgem, in co-ordination with retailers, users and the national system operator. In other countries, such as Chile, enabling the smart deployment of distributed energy resources, including EVs, may first require legal changes to the structure and business model of regulated network operators.

The European Union Clean Energy Package for all Europeans, under Article 32 of the directive for the internal market in electricity (recast), "mandates member states to provide the necessary regulatory framework and incentives to allow DSOs to procure flexibility services […] in accordance with transparent, non-discriminatory and market-based procedures in a market-based manner […]" from resources such as distributed generation, demand response or storage, as an alternative to system grid expansion (European Union, 2019a, 2019b). At a national level, new business models and regulatory changes may be needed to balance the benefits to the bulk power system and the distribution system, and to enable distribution network operators to take a more active role in electricity markets. While the necessary institutional and regulatory changes will vary by country, effective engagement between regulators, the power sector and transport stakeholders will be essential to identify and address the main regulatory barriers to enabling transparent, cost-effective and non-discriminatory EV integration.

Key findings:

- Vehicle charging may cause a substantial increase in electricity demand. However, limited impacts are expected on the operation of bulk power systems from both a generation and transmission perspective. EVs could account for 4% of global electricity demand by 2030 in the Sustainable Development Scenario (IEA, 2020a) or 25% of US electricity demand by 2050 in a high electrification scenario (Mai et al., 2018) to put the transport sector on track to meet the Paris Agreement decarbonisation goals.

- The way in which EVs integrate with and affect local distribution systems is likely to vary greatly. Detailed analysis is needed to assess local distribution-level impacts and enable optimal integration. Local impacts depend on key aspects such as network characteristics and existing grid capacity, the number and location of EV charging events, and the charging strategy.
- EV charging flexibility creates several opportunities to mitigate potential impacts on bulk and distribution systems, including ancillary services provision, improved integration of VRE into power systems and the supply of electricity onto the grid during peak times. These could reduce total electricity costs.
- Tapping EV charging flexibility requires charging infrastructure to be strategically located (e.g. at workplaces) and mechanisms to enable and compensate off-peak or co-ordinated charging. This controllability can be integrated in the EV or in the charging station. The solution chosen may depend on the EV fleet technology. However, with the introduction of harmonised and interoperable standards, basic functions with minimal cost can already reap large benefits.
- The flexibility of EV charging can be leveraged to minimise local impacts, but current business models and institutional barriers may limit the effective integration of EVs and VRE generation at the distribution level.
- Well-designed incentive programmes are necessary to compensate users for providing flexibility and ancillary services. Network owners, TSOs or regulatory authorities should provide efficient signals and regulations, while suppliers and aggregators should make it simple for final users to actively participate.
- The costs of implementing flexibility technologies (on-board systems, charging infrastructure, utility upgrades, communications) will need to be shared equitably. This calls for a co-ordinated and innovative approach involving stakeholders and policy makers, so all stakeholders along the flexibility value chain realise benefits.

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