IRENA
International Renewable Energy Agency

INNOVATION OUTLOOK

SMART CHARGING FOR ELECTRIC VEHICLES

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SUMMARY FOR POLICY MAKERS

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and fi nancial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. ***www.irena.org***

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Report contributors: Arina Anisie and Francisco Boshell (IRENA) with Pavla Mandatova, Mireia Martinez, Vincenzo Giordano and Peter Verwee (Tractebel).

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SUMMARY FOR POLICY MAKERS

The advent of electric vehicles (EVs) promises to be a game-changer for the world's shift to sustainable energy and particularly to renewable power generation. This is true for several reasons. Most notably, along with transforming the transport sector, EVs present a viable opportunity to introduce much higher shares of renewables into the overall power generation mix.

EV charging can create significant additional electricity demand. This can be met practically and cost-effectively with renewables, including solar and wind power fed into the grid. Such developments offer a tantalising prospect – particularly for cities – to decarbonise transport while also cutting air and noise pollution, reducing fuel import dependence and adopting new approaches to urban mobility.

Steady cost reductions for renewable power generation make electricity an attractive low-cost energy source to fuel the transport sector. Scaling up EV deployment also represents an opportunity for power system development, with the potential to add much-needed flexibility in electricity systems and to support the integration of high shares of renewables.

What makes EVs a unique innovation, from an electricity system perspective, is that they were not developed for the power sector and are not primarily a grid flexibility solution. Instead, their primary purpose is to serve mobility needs. Achieving the best use of EVs, therefore, requires a close look at which use cases would align best for both sectors. Optimally, EVs powered by renewables can spawn widespread benefits for the grid without negatively impacting transport functionality.

Cars, including EVs, typically spend about 95% of their lifetime parked. These idle periods, combined with battery storage capacity, could make EVs an attractive flexibility solution for the power system. Each EV could effectively become a micro grid-connected storage unit with the potential to provide a broad range of services to the system. At the same time, however, uncontrolled charging could increase peak stress on the grid, necessitating upgrades at the distribution level.

Emerging innovations in smart charging for EVs span not just technologies but business models and regulatory frameworks (IRENA, 2019a). These will be crucial to integrate renewable energy sources while avoiding network congestion. In addition, this innovation outlook discusses the possible impact of the expected mobility disruptions, including mobility-as-a-service and the widespread arrival of fully autonomous vehicles in the coming two to three decades.

This innovation outlook investigates the complementarity potential between variable renewable energy (VRE) sources – solar photovoltaics (PV) and wind power – and EVs. It considers how this potential could be tapped through smart charging up to mid-century.

Harnessing synergies between EVs and solar and wind power

According to Germany's Centre for Solar Energy and Hydrogen Research (ZSW), there were 5.6 million EVs on the world's roads at the beginning of 2019. China and the United States were the largest markets, with 2.6 million and 1.1 million EVs, respectively. If most of the passenger vehicles sold from 2040 onwards were electric, more than 1 billion EVs could be on the road by 2050 (see Figure S1). IRENA analysis indicates that future EV battery capacity may dwarf stationary battery capacity. In 2050, around 14 TWh of EV batteries would be available to provide grid services, compared to 9 TWh of stationary batteries (IRENA, 2019b).

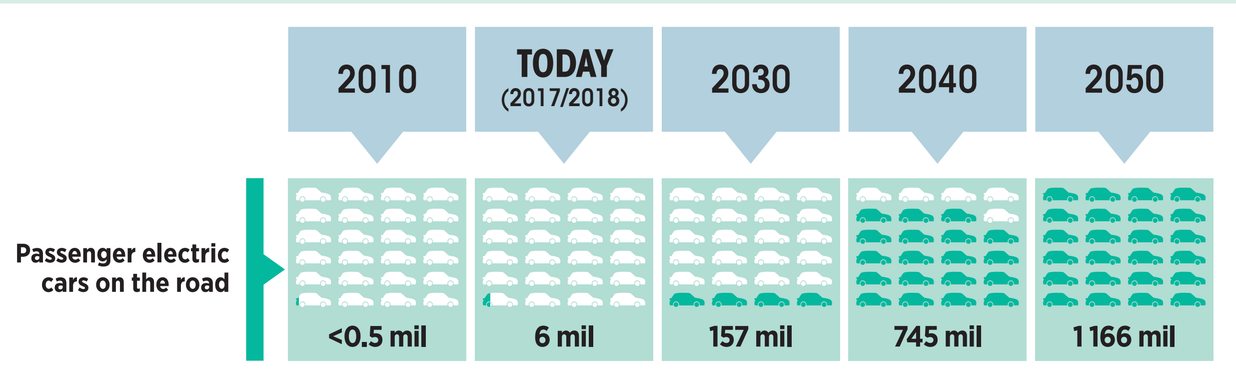
EV fleets can create vast electricity storage capacity. However, optimal charging patterns will depend on the precise energy mix. EV integration differs in systems with high shares of solar-based generation compared with systems where wind power prevails. If unleashed starting today, the use of EVs as a flexibility resource via smart charging approaches would reduce the need for investment in flexible, but carbon-intensive, fossil-fuel power plants to balance renewables.

Smart charging means adapting the charging cycle of EVs to both the conditions of the power system and the needs of vehicle users. This facilitates the integration of EVs while meeting mobility needs.

Smart charging allows a certain level of control over the charging process. It includes different pricing and technical charging options. The simplest form of incentive – *time-of-use pricing* – encourages consumers to defer their charging from peak to off-peak periods. More advanced smart charging approaches, such as direct control mechanisms will be necessary as a long-term solution at higher penetration levels and for delivery of close-to-real-time balancing and ancillary services. The main forms of such charging include V1G, V2G, V2H and V2B (see Abbreviations), as explained in Figure S2.

Each type of approach unlocks different options to increase the flexibility of power systems and to support the integration of VRE, mainly wind and solar PV. Figure S3 summarises the link between smart charging approaches today and the provision of flexibility in power systems. It shows how more advanced smart charging approaches might unlock greater flexibility in the system.

Figure S1: Growth in EV deployment between 2010 and 2050 in a Paris Agreement-aligned scenario



Source: IRENA, 2019b.

1 www.zsw-bw.de/en/newsroom/news/news-detail/news/detail/News/global-e-car-count-up-from-34-to-56-million.html

Figure S2: Advanced forms of smart charging

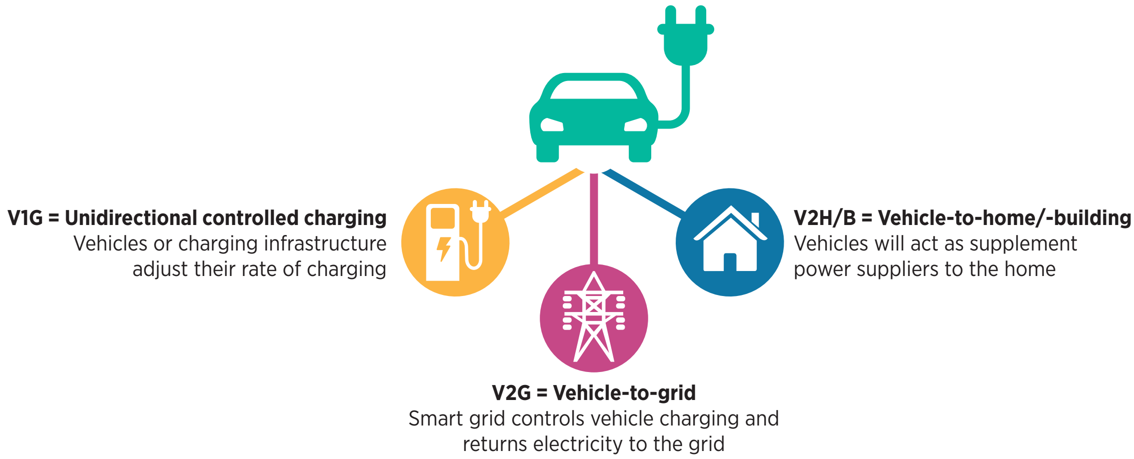
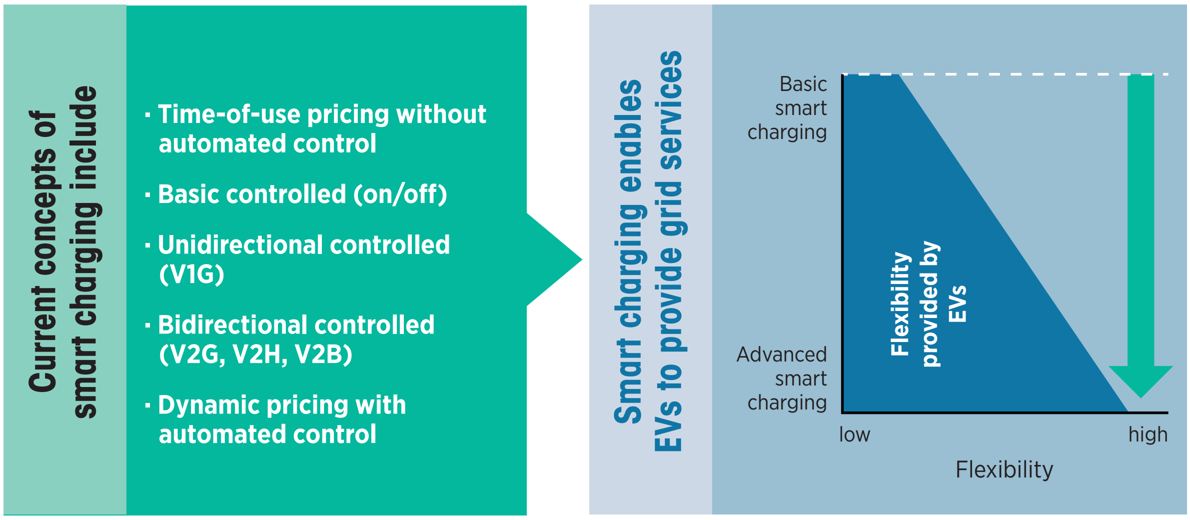


Figure S3: Smart charging enables EVs to provide flexibility



Flexibility services provided by EV smart charging

Smart charging could provide flexibility at both the system and local levels (see Figure S4). At the system level, smart charging could facilitate balancing in the wholesale market. With V1G, the EV charging patterns could be controlled to flatten peak demand, fill load valleys and support real-time balancing of the grid by adjusting their charging levels. With V2G, by injecting electricity back to the grid, EVs also could provide ancillary services to transmission system operators. Smart charging could help distribution system operators manage congestion and could help customers manage their energy consumption and increase their rates of renewable power self-consumption.

The Danish project, Parker, is an example of a V2G project that uses smart charging technology and relies on cooperation between automotive and power industries to demonstrate the ability of electric vehicles to support and balance power systems based on renewable energy. Grid integration specialists such as Enel, Nuvve and Insero, as well as car manufacturers Nissan, Mitsubishi and PSA Groupe have demonstrated that state-of-the-art vehicles from various car brands can contribute to supporting the electricity grid, providing services such as frequency and voltage control via V2G technology (Bach Andersen, 2019).

Impact of EV charging on electricity systems in cities

EV charging shapes overall energy demand patterns and influences the best choices for urban grid development.

Energy consumption and peak demand

Uncontrolled EV charging causes only slight increases in electricity production and consumption, as shown in several studies (Eurelectric, 2015; BoA/ML, 2018a; Schucht, 2017). However, the impact on peak demand can be much greater. In a scenario for the United Kingdom (UK) of 10 million EVs by 2035, evening peak demand would increase by 3 gigawatts (GW) with uncontrolled charging, but it would increase by only 0.5 GW if charging is smart (AER, 2018). Other such examples can be found in Figure S3.

Electricity infrastructure

If more than 160 million EVs come into the power system by 2030 (IRENA, 2018), and high numbers were concentrated in certain geographical areas with their charging uncontrolled, the local grid would be affected by congestion. To avoid such a situation, reinforcement of the local grid would be required. With smart charging, such investments can largely be avoided. Smart charging would tend to be combined with slow charging

Figure S4: Potential range of flexibility services by EVs

SYSTEM FLEXIBILITY		LOCAL FLEXIBILITY	
Wholesale market	**Transmission System Operator**	**Distribution System Operator**	**Behind-the-meter**
• Peak-shaving • Portfolio balancing	• Frequency control • (primary, secondary and tertiary reserve) • Other ancillary services (*e.g.*, voltage management, emergency power during outages)	• Voltage control • Local congestion and capacity management	• Increasing the rate of Renewable Energy self-consumption • Arbitrage between locally produced electricity and electricity from the grid • Back-up power

Smart charging reduces the costs associated with reinforcing local electricity grids. Unlike uncontrolled charging, it decreases simultaneity and lowers peaks in demand.

in low-voltage distribution networks. For example, the local distribution system operator in Hamburg, Germany carried out an analysis and concluded that a 9% EV share would lead to bottlenecks in 15% of the feeders in the city's distribution network. To avoid this, a smart charging solution was adopted, and the distribution system operator is currently installing control units to monitor charging point loads (Pfarrherr, 2018).

Slow chargers – typically up to 22 kilowatts (kW) – are used mostly for home and office charging. With slow charging the EV battery is connected to the grid for longer periods of time, increasing the possibility of providing flexibility services to the power system.

Fast chargers – typically 50 kW and up – are likely to be used in direct current (DC) systems, often along highways although some cities are also deploying them for street charging (*e.g.*, Paris' Belib).

Ultra-fast chargers – above 150 kW – will soon be available, helping to overcome customer anxiety about electric mobility and acting as a crucial complement to home- and office-based slow charging.

Fast and ultra-fast charging does not leave batteries connected to the system long enough to provide flexibility. The impact of fast charging on the grid will need to be mitigated by installing charging points in areas that have a low impact on local peak demand and congestion. Also, combining fast-charging infrastructure with locally installed VRE and stationary energy storage can, through buffering, increase the flexibility of the station vis-à-vis the grid. Battery swapping may gain further importance at least for selected applications (*e.g.*, buses) or in certain parts of the world (*e.g.*, China). Effectively "decoupling the battery from the wheels" may present further opportunities for the grid. The combination of transport and renewable power innovations also promises to reduce energy costs for the user.

Impact of EV smart charging on VRE integration

In this analysis, a modelling exercise was conducted to study the benefits of smart charging at the system level, for both system operation in the short term and system expansion in the long term. The results of this exercise aim to indicate just the magnitude of the smart charging benefit in the power systems, and the exact numbers should not be considered as generally valid. The smart charging impact depends on each power system's characteristics and smart charging implementation.

Smart charging reduces the costs associated with fast and ultra-fast charging are priorities for the mobility sector. Yet, slow charging is best suited for the "smart" approach that boosts system flexibility. But solutions like battery swapping, charging stations with buffer storage, and nighttime charging for EV fleets can help to avoid peak-demand stress from fast and ultra-fast charging. reinforcing local electricity grids. Unlike uncontrolled charging, it decreases simultaneity and lowers peaks in demand.

Table S1: Impact of charging according to type

	Electricity demand	Peak demand	Distribution grids
Slow charging, uncontrolled	⊕	⊕⊕	⊕⊕
Slow charging + smart charging	⊕	⊕	⊕
Fast charging	⊕	⊕⊕	⊕⊕
Fast charging with batteries	⊕	⊕	⊕

Short-term impact

The short-term operation analysis, which assessed the impact of different vehicle-grid integration strategies in isolated systems with high solar irradiation, clearly demonstrated the benefits of smart charging versus uncontrolled charging. As illustrated in Figure S5, the implementation of unidirectional smart charging (V1G) and bidirectional smart charging (V2G) gradually reduces curtailment down to zero levels. Consequently, carbon dioxide (CO_2) emissions in the system are somewhat reduced, due to an increased share of solar generation to cover the loads. Thanks to the spreading out of charging over the day, peak load is reduced in both V1G and V2G. The average cost of generating electricity may fall.

Long-term impact

The long-term analysis considered system expansion with the optimal capacity mix according to wholesale electricity prices, and investing in the new assets to meet demand in 2030. Both solar-based and wind-based isolated systems were studied. The analysis revealed increased investment in renewables and consequently increased renewable power production, especially for solar with V2G.

Smart charging provides greater benefits to systems high in solar PV than wind, due to the more predictable generation profile from solar. Systems with high shares of wind might already show a correlation between power production and EV charging, even with uncontrolled charging.

Solar PV generation profiles do not usually match with uncontrolled EV charging, except for office charging and in part also public charging during the day. The incremental benefits of smart charging in terms of impact on renewable capacity could thus be high with solar, mainly with the use of affordable batteries that can store excess renewable power that is not consumed during the day, and then dispatch this power later. For wind, there already might be a high match between wind power production and EV charging profiles, even with uncontrolled EV charging, as wind generation may occur at night, the time commonly used for EV charging. Consequently, yearly peak load decreases similarly to the short-term analysis. Boosting either solar or wind power in the system sharply reduces CO_2 emissions. Figure S6 illustrates the results of the analysis.

Figure S5: Short-term impact of EV charging

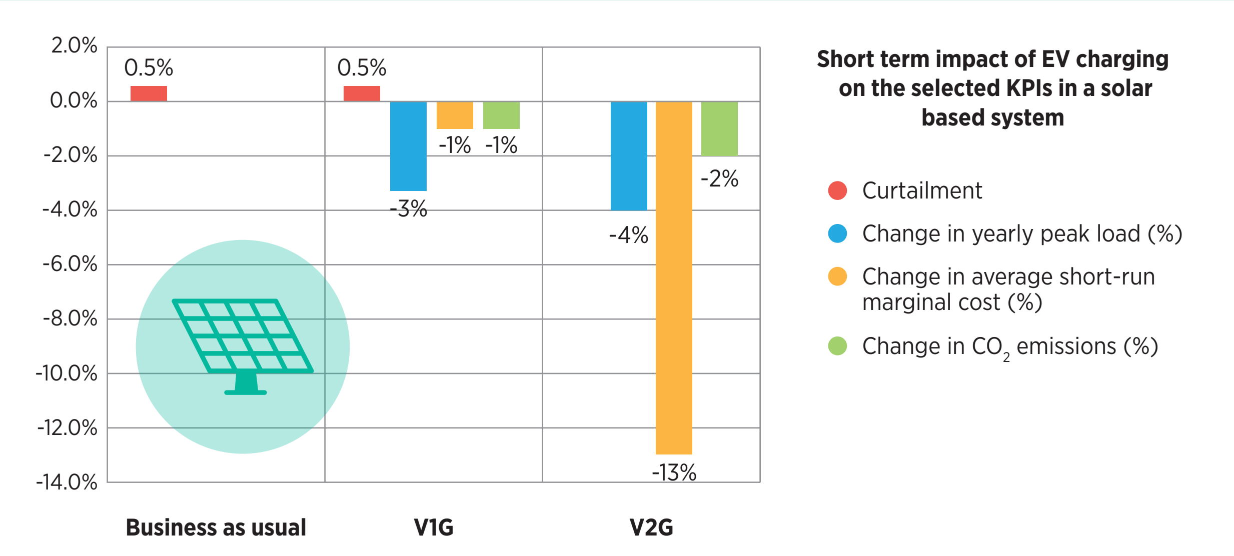
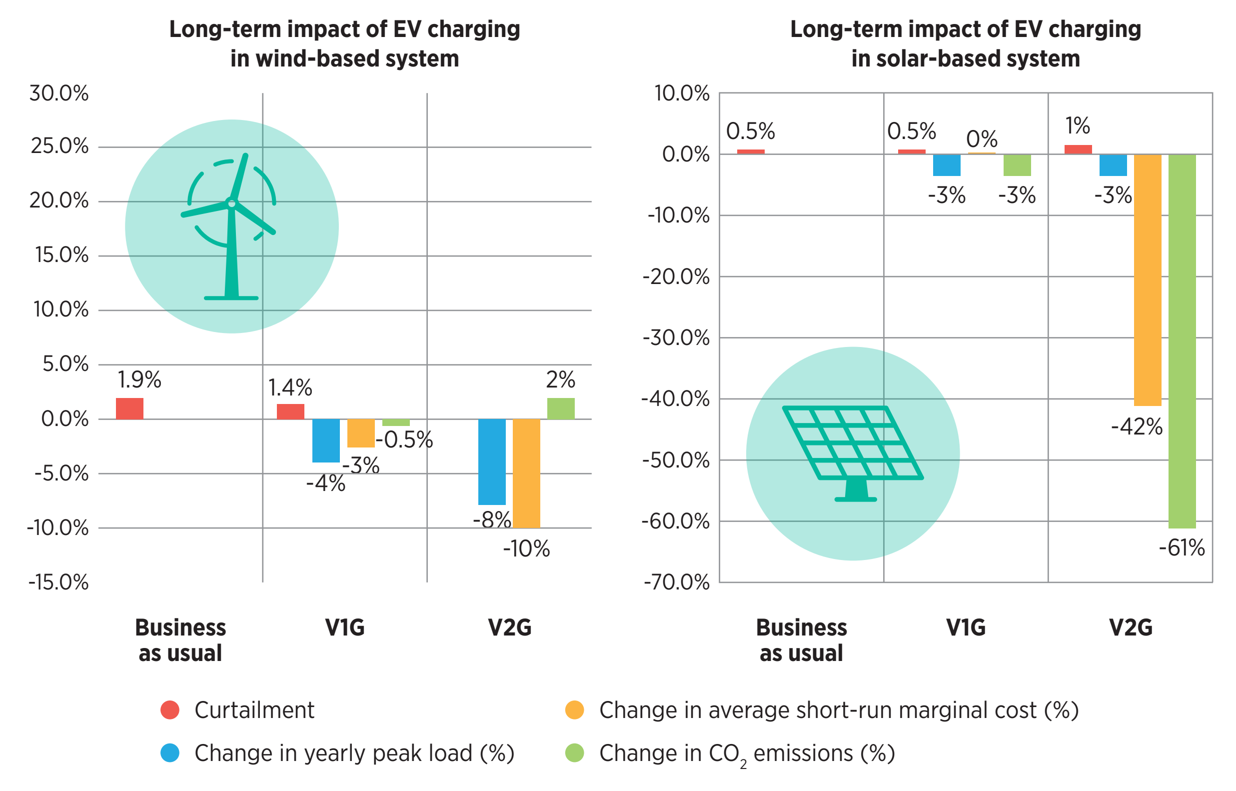


Figure S6: Long-term impact of EV charging



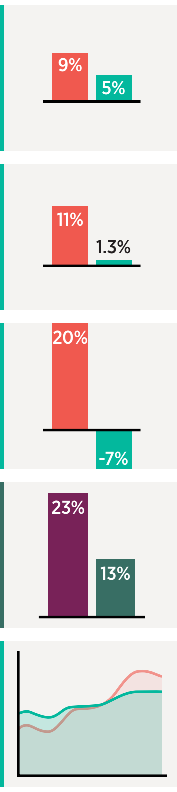
Smart charging cuts peak load, reduces curtailment and allows higher shares of low-cost PV electricity. This can help to displace more expensive generation and lower electricity prices.

The decrease in CO_2 emissions is driven by growing shares of renewable energy in the system in both the solar and wind smart charging cases. The decrease in the short-run marginal cost also largely follows the rising shares of renewables. High variations in curtailment are observed when V1G or V2G are modelled.

IRENA's innovation outlook is consistent with results from similar studies looking at the impact on smart charging in VRE integration. Other studies have identified a beneficial impact of smart charging on peak load mitigation in the system and related CO_2 emissions (Chen and Wu, 2018; RMI, 2016; Taljegard, 2017) and renewable curtailment mitigation (McKenzie *et al.*, 2016). These are summarised in Figure S7.

Figure S7: Impact of EV smart charging on the electricity grid

Study	Scenario	Uncontrolled charging	Smart charging
IRENA	**50%** penetration in an isolated system with 27% solar share	**↑9%** increase in peak load 0.5% solar curtailment	**↑5%** increase in peak load (V2G) Down to 0% curtailment
RMI, 2016	**23%** penetration US (California, Hawaii, Minnesota, New York, Texas)	**↑11%** increase in peak load	**↑1.3%** increase in peak load (V1G)
Taljegard, 2017	**100%** penetration Denmark, Germany, Norway & Sweden	**↑20%** increase in peak load	**↓7%** decrease in peak load (V2G)
McKenzie, 2016	**50%** penetration in Island of Oahu, Hawaii, US 23% VRE share	**10-23%** VRE curtailment without EVs	**8-13%** VRE curtailment with smart charging EVs
Chen and Wu, 2018	**1 MILLION** EVs in Guanzhou region, China	**↑15%** increase in peak load	**↓43-50%** reduction in valley/peak difference



- Peak load with uncontrolled charging
- Peak load with smart charging
- Curtailment in no EVs scenario
- Curtailment with smart charging EVs

Mobility-as-a-service less compatible with EV-based flexibility

Car sharing and car pooling are already changing the habits of consumers. Shifting away from vehicle ownership to shared mobility and to mobility-as-a-service (MaaS) is expected to continue progressively with digitalisation. Fully autonomous vehicles, which are projected to take off at larger scales in urban environments around 2040, will drive this trend further. Most of these vehicles will be electric.

This evolution should be most notable in cities, which are projected to be home to 60% of the world population by 2030 and 70-80% by 2050. The extent of this impact will depend on economic development and population density. Eventually, the proliferation of MaaS combined with autonomous driving may slow sales of EV light-density vehicles in densely populated cities (sales of two-wheelers may be less affected). At the same time, the EV driving range will increase and off-peak transport will continue to occur during the night.

Consequently, the net available flexibility in the system might decrease, especially during the daytime, for balancing solar power. The increased daily distances travelled per car will imply reduced parking time – that is, less battery capacity for grid services. The implications for the availability of EV flexibility – which may decrease in a future system based on shared autonomous vehicles compared to a transport system based on individual EV ownership – needs to be studied in detail. In the meantime, however, EV-based smart charging can be a crucial factor to scale up variable renewable power.

MaaS could work against VRE integration, as fewer EV batteries connect to the grid. With major mobility-sector disruption, EVs might not provide as much grid flexibility.

EV smart charging outlook to 2050

The evolution of the flexibility that an EV can provide to the grid though smart charging is summarised in Figure S8. By 2030, flexibility from EVs could increase dramatically if the market uptake is facilitated by ambitious political targets and the availability of smart charging capabilities. Cars with 200 kilowatt-hour (kWh) batteries and a range of up to 1 000 kilometres may appear on the roads between 2030 and 2050. However, the scale of their deployment will depend on the weight and cost of these batteries, as the need for such ranges will remain limited.

Ultra-fast charging power of 600 kW may be available eventually but would still be used to a limited extent. By 2050, mobility-as-a-service and autonomous vehicles will disrupt mobility and most likely flatten out the rise in available flexibility in the system. The parking time of shared vehicles may be reduced and focus mostly in hubs in city suburbs, decreasing the flexibility available for balancing solar power.

Policy priorities

Besides deploying more renewables, countries need to set ambitious transport targets. In addition to mobility targets and CO_2 standards that are already in place in some countries, CO_2 reduction targets for transport could be considered.

Introducing (where not in place yet) temporary incentives for EVs is relevant to kickstart the EV market. As direct monetary incentives are phased out in response to local circumstances and needs, non-monetary incentives should eventually become more prevalent.

Governments and local authorities in nascent EV markets should also design incentives for smart charging infrastructure. For example, in United Kingdom, from July 2019, only home chargepoints that use 'smart' technology will be eligible for government funding under the Electric Vehicle Homecharge Scheme. (RECC, 2019). All governments should address complex market segments such as ultra-fast charging and multi-unit dwellings.

Regulatory priorities

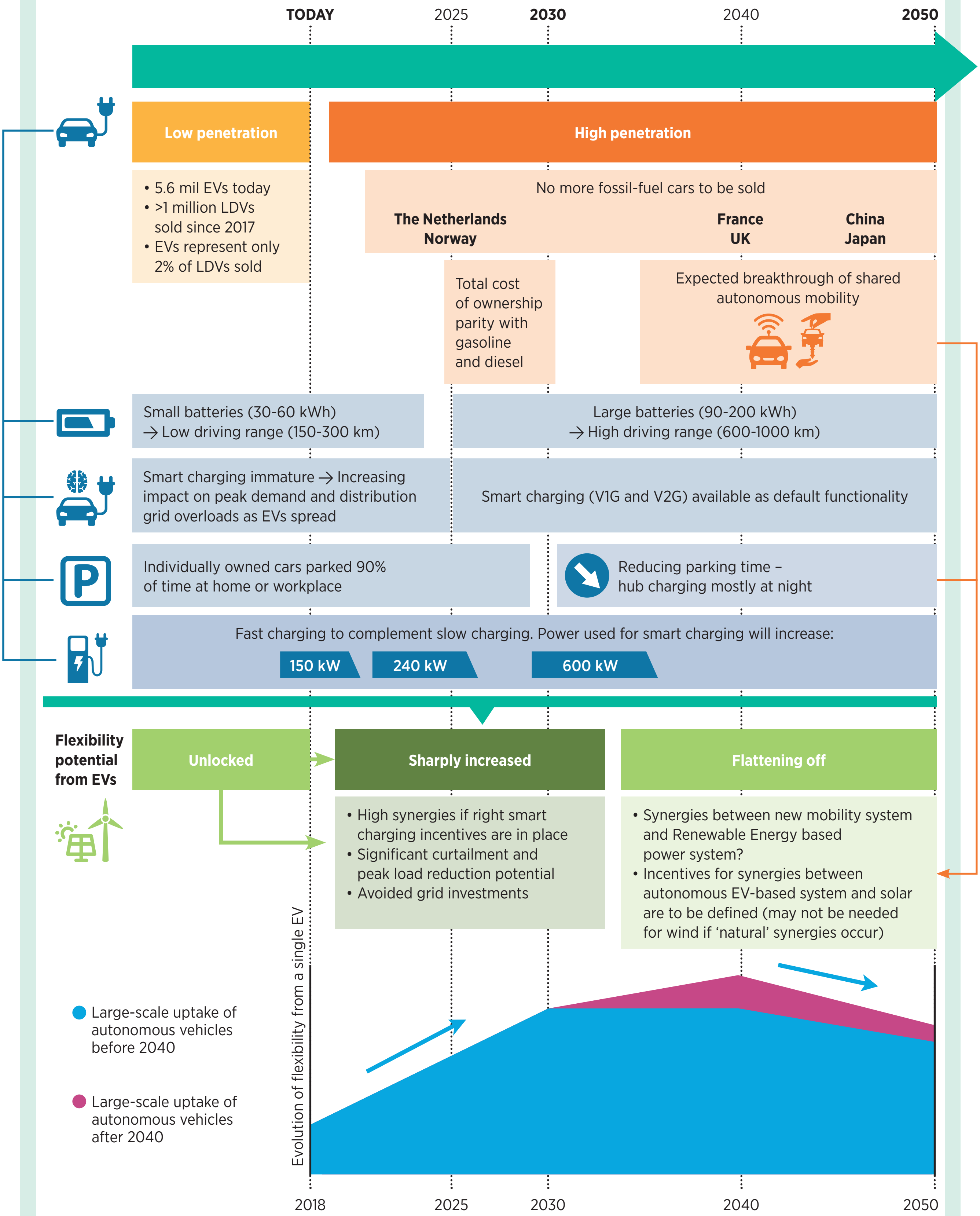
The key regulatory aspects that are needed include implementing, initially, time-of-use tariffs and then eventually dynamic prices for EV charging, allowing EVs to participate in ancillary service markets, enable value stacking and avoiding double charges.

First, appropriate price signals are a key enabler for the implementation of smart charging. Price signals to EV users would make it possible to shift the demand for EV charging to off-peak periods and to match it with the availability of renewable energy sources. Customers will not be able to match their EV charging with VRE generation if they do not receive corresponding price signals to do so. Increasing automation will enable both drivers and service providers to manage this system. Several retailers, mainly in the United States, have adopted EV home charging tariffs, offering charging rates up to 95% lower at night compared to during the day (BNEF, 2017e).

Retail electricity pricing for EV users must reflect the actual electricity mix – that is, low wholesale prices when abundant VRE is available at close to zero marginal cost, for EVs to charge at those moments as much as possible. Dynamic pricing and the updating of distribution grid tariffs will be necessary to signal to the vehicles the best moments to charge and discharge (in case of V2G). For that to happen, functioning wholesale and retail markets must be put in place worldwide, which is not the case today even in the top 10 e-mobility markets. Retail price regulation is often a highly politically sensitive issue.

Second, having a single revenue stream will likely be insufficient to make a business case for V2G in particular. In other words, the batteries will have to "stack" the revenue by serving multiple applications, providing services to both system level and locally, as shown in Figure S4. For this to materialise, there are a number of prerequisites besides dynamic pricing. In many places, competitive balancing/ancillary services

Figure S8: Evolution of EV flexibility and renewable energy integration by 2030 and 2050



Illustrative outlook of available flexibility from a single electric light-duty vehicles in an urban context

Regulations should allow EV batteries to provide different services to the power system, encouraging stacking of services and revenues. But double levies for V2G charging need to be avoided. Taxes and grid charges should be applied only to the net energy transferred for the purpose of driving.

markets are absent, and local grid operators are not allowed to manage congestion in their grids in ways other than by reinforcing the grid. Aggregated EVs will need to have access to these markets and to several markets in parallel.

Excessive fees for to EV smart charging can discourage uses that provide system-wide benefits. This can occur through double taxation – such as collection of fees both for charging a vehicle and for injecting power to the grid – and network charges when electricity is consumed from and supplied to the grid with V2G technology.

Business models

Business models need to account for the needs of the power system (remuneration from providing services to power systems) as well as of the vehicle owner (mobility and preserving the condition of the vehicle and the battery). Parameters such as speed of charging, the health of EV batteries, potential reduced battery lifetimes and others must therefore be monitored. These should be taken into account when determining the smart charging business model. For example, providing operation services would require the battery to act "on call" while receiving stable revenues just for being available. On the other hand, electricity price arbitrage requires repetitive charge and discharge, which greatly reduces the battery life.

EV batteries can provide the fast response needed for some ancillary services, but their power capacity is limited; thus a single EV cannot provide these services for the period of time needed by the power system. However, when EVs are aggregated they can complement one other, resulting in a virtual power plant with a fast response and the ability to provide services for the needed period of time.

Aggregator business models facilitate the use of EVs as a source of flexibility. At least 1-2 MW capacity must be traded to make EV power provision viable at the wholesale level. This requires the aggregation of around 500 vehicles and their charging points.

Virtual Power Plant operator Next Kraftwerke, and Jedlix, an electric vehicle (EV) aggregator and smart charging platform provider, have launched an international pilot project which uses EV batteries to deliver secondary control reserve to TenneT, the transmission system operator in Netherlands. Jedlix will be able to combine user preferences, car data, and charging station information to provide a continuous forecast of the available capacity. This is then used by Next Kraftwerke in the bidding process of TenneT for procuring grid services (NextKraftwerke, 2018).

Technology priorities

Smart charging should be developed while keeping in mind the specificities of each power system. The smart charging strategy may differ depending on the VRE source that dominates the power system and its generation profile.

The incremental benefits of smart charging will be particularly significant in solar-based systems. By shifting charging to better coincide with solar PV generation, and by implementing V2G, increased shares of solar could be integrated at the system level and the local grid level, mitigating the need for investments in the distribution grid. For EV charging to complement solar, charging must shift to mid-day, which also means that charging stations must be located at workplaces and other commercial premises where EV owners park their vehicles during the day. Employees may be able to use free renewable electricity for charging at the office (and then later use renewable power at home for V2H). For that, pre-cabling and smart chargers should be promoted at commercial buildings.

Wind production profiles are more region specific. In some regions, these profiles may match well with EV charging profiles, even if EVs are charged in an uncontrolled way, because wind may blow more in the evening and at night when EVs tend to be charging. In such systems, the focus should be mainly on home charging at night and on adjusting dynamically to variations in wind production.

These strategies will need to be further adjusted with the increase in mobility-as-a-service and the eventual shift towards fully autonomous vehicles, mainly in urban areas. EVs will remain primarily a means for transport and will serve only secondarily as "batteries for the system". This would not only drive the development of new technologies such as wireless charging, but also move charging from home/office to hubs. The implications for the availability of EV flexibility – which may decrease in a future system based on shared autonomous vehicles compared to a transport system based on individual EV ownership – have to be carefully studied.

Moreover, currently only very few charging stations (both home and public) are smart grid enabled (Deloitte, 2017), and very few cars allow for V2G. Rising EV penetration will further increase the need for common standards for charging infrastructure and interoperable solutions between charging stations, distribution networks and the EVs themselves. Interoperability is key not only to shield from charging infrastructure vendor lock-in but also to allow for cost-effective connectivity of EVs with diverse charging infrastructure and metering.

Communication protocols must be standardised, while V2G charging stations and control systems have to be interoperable.

Table S2: Charging needs according to city type

	Privately owned cars	Shared mobility	Public transport	Two-wheelers	Prevailing type of charging
Low-income, dense metropolitan areas			⊕⊕	⊕⊕	Public charging, hubs for buses
High-income suburban sprawl	⊕⊕	⊕	⊕		Home charging
High-income, dense metropolitan areas	⊕	⊕⊕			Charging hubs, more fast charging

Policy checklist

Figure S9: Policy checklist

Recommendations	Action list	
• Promote renewable energy to decarbonise power system • Promote EVs to decarbonise transport	1 Set ambitious targets	• Targets for different transport types • CO_2 reduction targets
	2 Support charging infrastructure	• Public charging, fast charging, multi-unit dwellings
	3 Keep or introduce temporary incentives for cars	• Monetary vs other advantages
	4 Deploy more renewables	• Ambitious renewable energy targets
• Focus on smart charging • Create incentives to tap large incremental benefits, especially from solar use	5 Standardise and ensure interoperability	• V2G standards and interoperability between EVs and supply equipment
	6 Implement on islands and in areas with high shares of renewable energy	
	7 Design smart charging strategy to fit the power mix	• Workplace and commercial charging will be key for 'solar-based systems' • Potential synergies between home charging for 'wind-based systems', combined with home solar
	8 Choose optimal locations for charging	• Synergies between mobility and the grid
	9 Market design should allow for smart charging, adjust regulation	• Customer incentives • Avoid double payments of network charges and taxes • Enable revenue stacking for EVs in different markets
	10 Complement grid charging with storage at charging points or battery swapping	
• Study impact of long-term evolution of mobility on smart charging	11 Support battery and charging R&D considering both mobility and grid needs	
	12 Study implications of mobility-as-a-service for EV flexibility	
	13 Integrated planning of power and transport sector	• Build charging hubs in optimal locations

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