IRENA
International Renewable Energy Agency

INNOVATION OUTLOOK

SMART CHARGING FOR ELECTRIC VEHICLES

Supported by:

Federal Ministry
for the Environment, Nature Conservation
and Nuclear Safety

based on a decision of the German Bundestag

ISBN 978-92-9260-124-9

Citation: IRENA (2019), *Innovation outlook: Smart charging for electric vehicles,* International Renewable Energy Agency, Abu Dhabi.

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 financial 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***

Acknowledgements

This report benefited greatly from the input and review of experts: Peter Bach Andersen (Technical University of Denmark), Petar Georgiev (Eurelectric), Gregory Poilasne (Nuvve), Johannes Henkel (50Hertz), Matteo Muratori (NREL), Christelle Verstraaten and David Colt (ChargePoint), Naotaka Shibata (TEPCO), Yasuo Matsunaga (Nissan), Tomoko Blech (CHAdeMO Association), Carlo Mol (VITO), Paolo Santi (MIT), Lysander Weiss (Venture Idea GmbH), Nikola Medimorec (SLoCaT), Alberto Piglia and Chiara dalla Chiesa (Enel), Hugo Pereira (EV Box), Patrick Wittenberg (Innogy), Lisa Wolf (former Eurelectric), Yue Xiang (Sichuan University, China), Xuewen Geng (State Grid EV Service Company), Mathias Wiecher (E.ON), Bastian Pfarrherr (Stromnetz Hamburg), Severine Allano and Francois Grossmann (Tractebel), Tomas Jil (former IRENA), Dolf Gielen, Alessandra Salgado, Bowen Hong, Emanuele Taibi, Carlos Fernández, Nicholas Wagner, Laura Gutierrez and Paul Komor (IRENA).

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

The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), through the International Climate Initiative (IKI), generously supported the preparation of this report. More information about IKI can be found on the website: ***www.international-climate-initiative.com/en***.

For further information or to provide feedback, please contact IRENA at: ***publications@irena.org***

Disclaimer

The views expressed in this report are the sole responsibility of the author/s and do not necessarily reflect the opinion of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Just as future transport must be increasingly electrified, future power systems must make maximum use of variable renewable energy sources. Smart charging minimises the load impact from electric vehicles and unlocks the flexibility to use more solar and wind power.

CONTENTS

Figures

Tables

Boxes

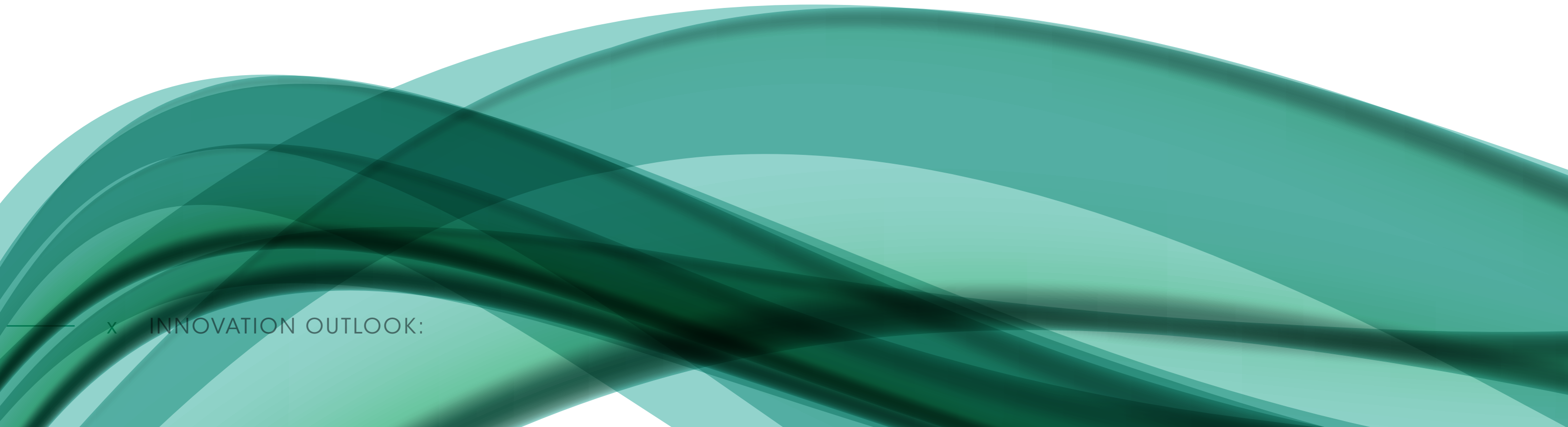
ABBREVIATIONS

A	Ampere
AC	Alternating current
AI	Artificial intelligence
BAU	Business as usual
B2B	Business-to-business
B2C	Business-to-customer
B2G	Business-to-grid
BEV	Battery electric vehicle
C-rate	Cycling rate
C2C	Customer-to-customer
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CCGT	Combined-cycle gas turbine
CEM	Clean Energy Ministerial
CEP	Clean Energy Package
CO_2	Carbon dioxide
DC	Direct current
DoD	Depth of discharge
DSO	Distribution System Operator
EoL	End of life
ERS	Electric road systems
EU	European Union
EUR	Euro
EV	(Plug-in) electric vehicle
EVSE	Electric vehicle supply equipment
EVSS	Electric Vehicle Subsidy Scheme
G2B	Grid-to-business
GBP	British pound
GW	Gigawatt
ICE	Internal combustion engine
ICT	Information and communications technology
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
km	Kilometre
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour

LCO	Lithium cobalt oxide
LDV	Light-duty vehicle
LFP	Lithium iron phosphate
Li-ion	Lithium ion
LMO	Lithium manganese oxide
LMP	Lithium metal polymer
LTO	Lithium titanate oxide
MaaS	Mobility-as-a-service
MW	Megawatt
MWh	Megawatt-hour
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt
OCGT	Ppen-cycle gas turbine
OCPP	Open Charge Point Protocol
OEM	Original equipment manufacturer
OPEX	Operating expense
PG&E	Pacific Gas and Electric
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
R&D	Research and development

REEV	Range extender
SaaS	Software-as-a-service
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SoC	State of charge
TCO	Total cost of ownership
TSO	Transmission System Operator
USD	United States dollar
V	Volt
V1G	Unidirectional power flow
V1X	Vehicle-to-everything (unidirectional)
V2B	Vehicle-to-building
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything (bidirectional)
VGI	Vehicle-grid integration
VRE	Variable renewable energy
Wh	Watt-hour
ZEBRA	Zeolite Battery Research Africa

Smart charging for electric vehicles holds the key to unleash synergies between clean transport and low-carbon electricity. Batteries in cars, in fact, could be instrumental to integrate high shares of renewables into the power system.



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).

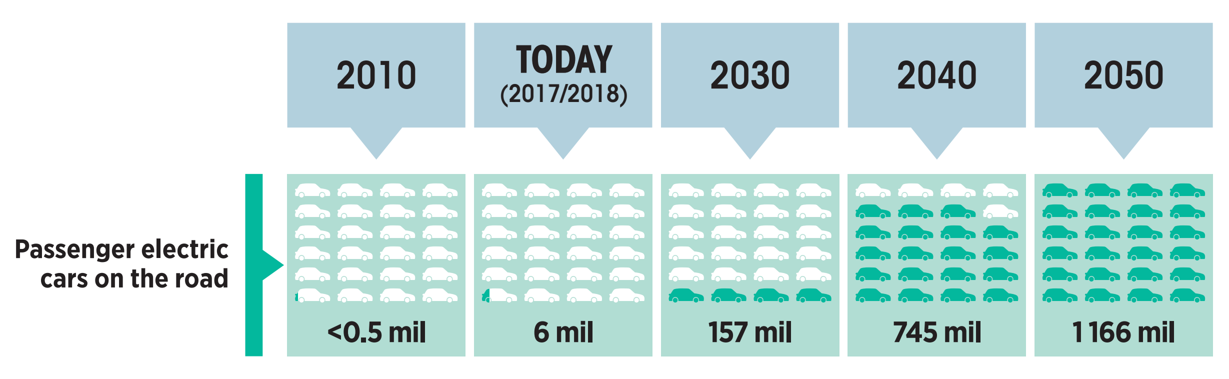
EV fleets can create vast electricity storage capacity. However, optimal charging patterns will depend on the precise energy mix. EV integration differs in systems with high shares of solar-based generation compared with systems where wind power prevails. If unleashed starting today, the use of EVs as 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

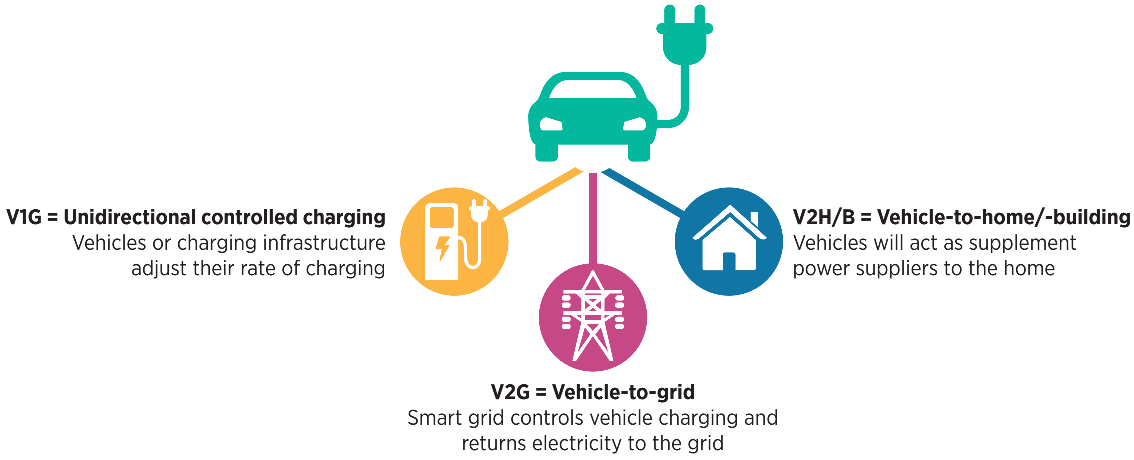
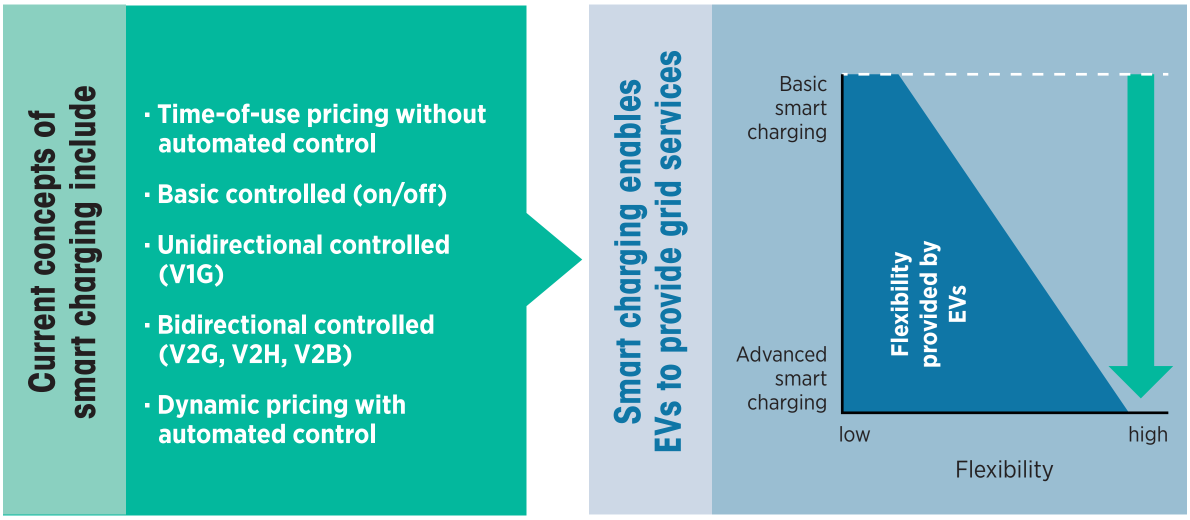


Figure S3: Smart charging enables EVs to provide flexibility



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.

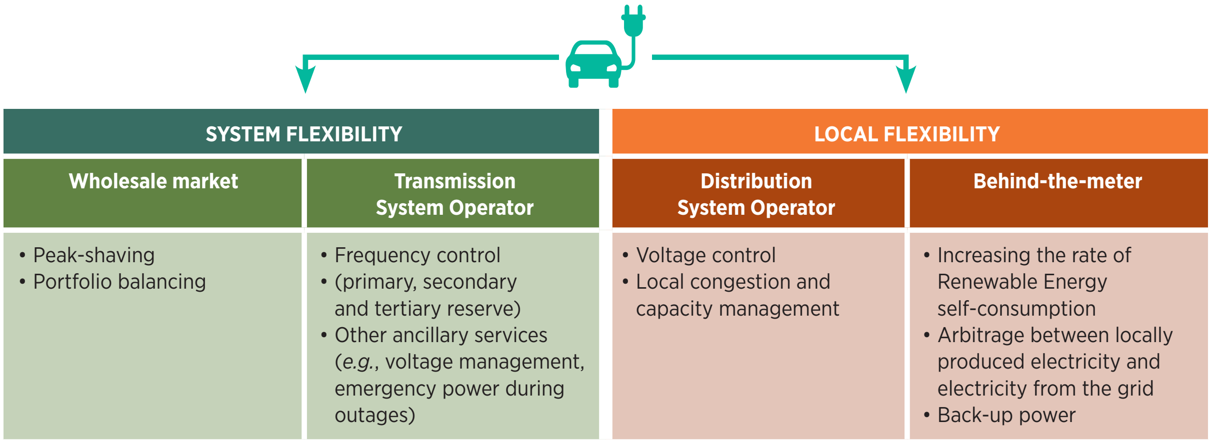
Energy consumption and peak demand

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

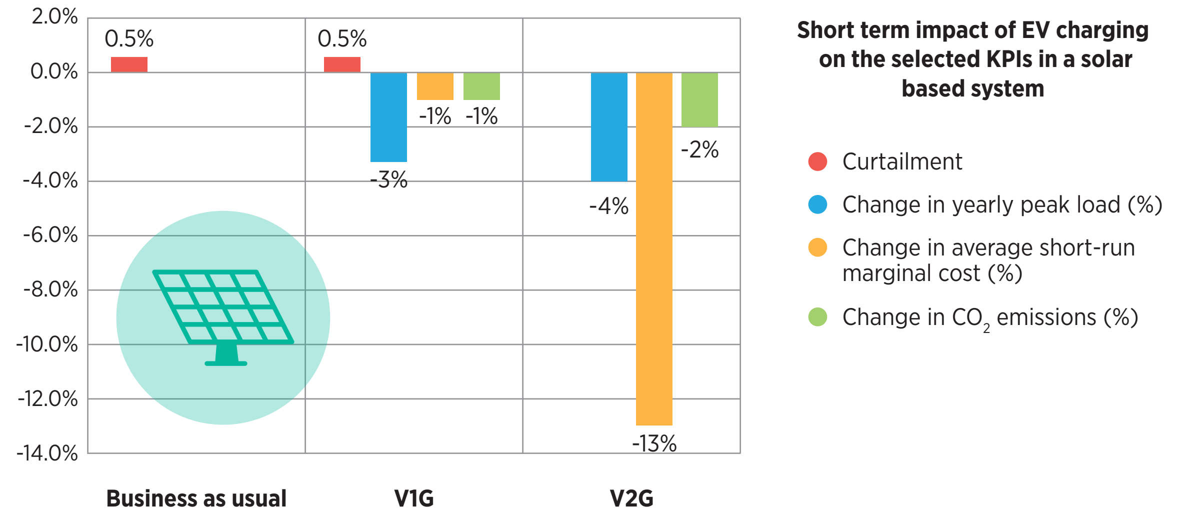
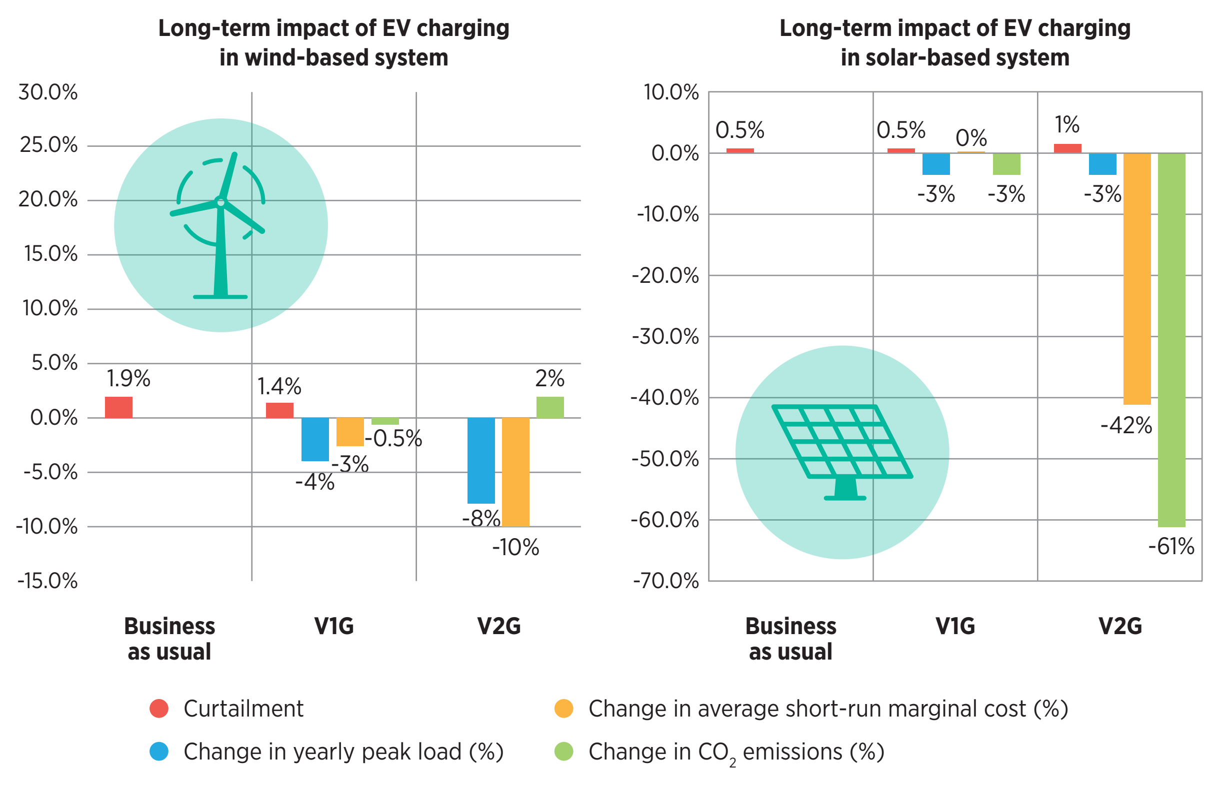


Figure S6: Long-term impact of EV charging

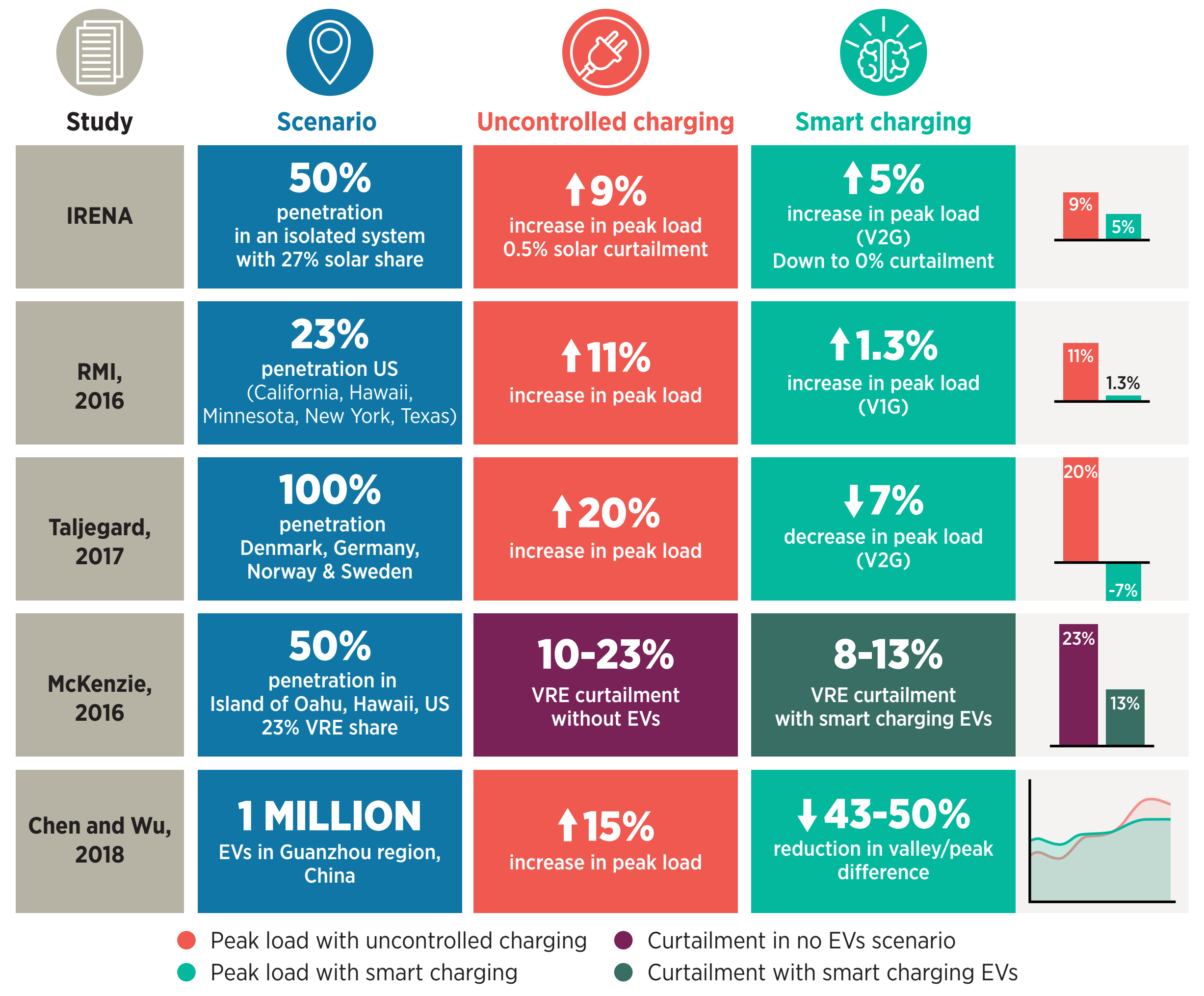


Smart charging cuts peak load, reduces curtailment and allows higher shares of low-cost PV electricity. This can help to displace more expensive generation and lower electricity prices.

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

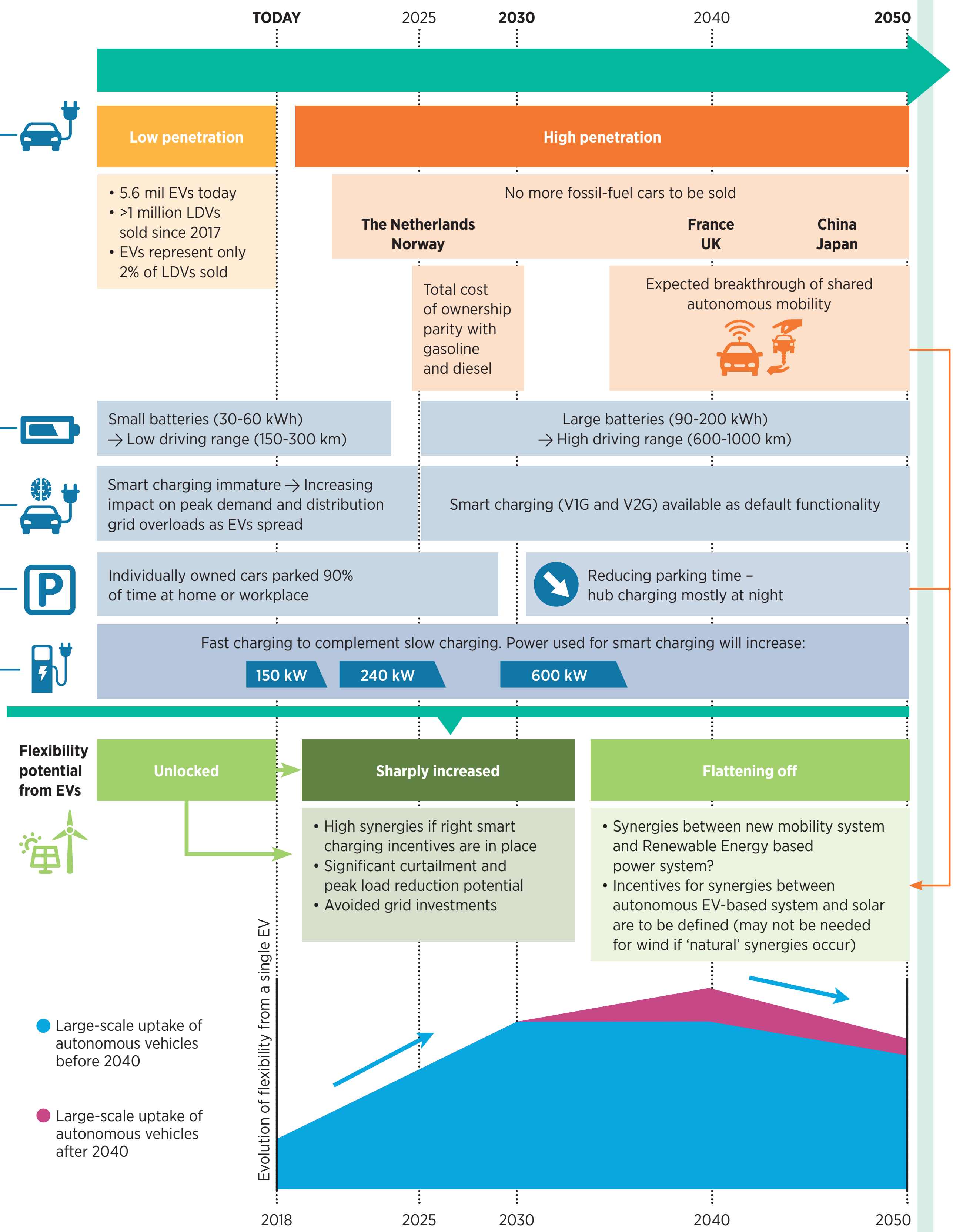
The key regulatory aspects that are needed include implementing, initially, time-of-use tariffs and then eventually dynamic prices for EV charging, allowing EVs to participate in ancillary service markets, enable value stacking and avoiding double charges.

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.

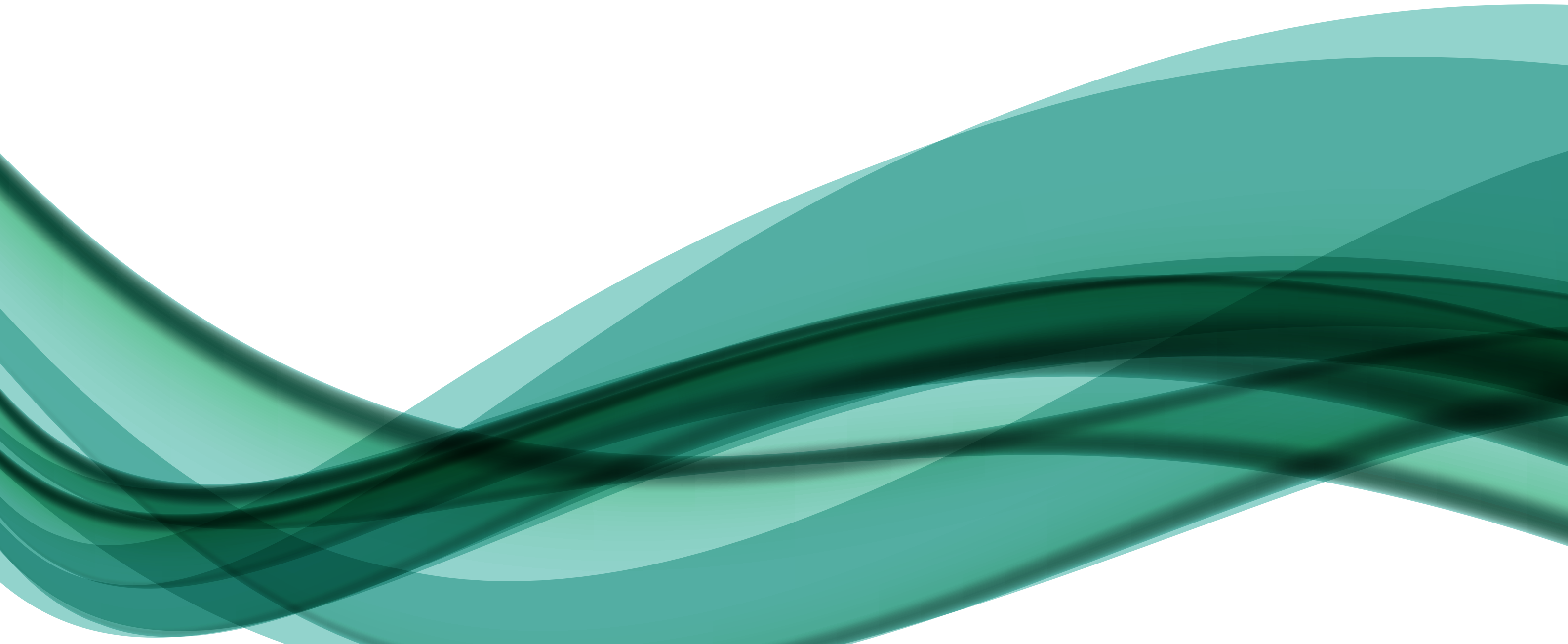
These strategies will need to be further adjusted with the increase in mobility-as-a-service and the eventual shift towards fully autonomous vehicles, mainly in urban areas. EVs will remain primarily a means for transport and will serve only secondarily as "batteries for the system". This would not only 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

1. INTRODUCTION

Future power systems will be increasingly based on variable renewables. Future transport systems will be increasingly electrified. The future may see an integrated, emissions-free electricity and transport system, with renewable energy powering not only grids but also electric vehicles (EVs). EVs represent a paradigm shift for both the transport and power sectors, with the potential to aid the decarbonisation of both sectors by coupling them. In an urban context, in particular, cities can benefit from decarbonising transport while greatly reducing air and noise pollution, as well as fuel imports, and providing new technology options to rethink urban mobility.

Steady cost reductions in renewable power generation make electricity an attractive low-cost fuel for the transport sector. A significant scaling up of EV deployment also represents an opportunity for the power system, with the potential to provide much-needed flexibility in a system with a high share of renewables. EVs are a unique innovation because, unlike other flexibility options, they have not been developed to serve the power system; instead, they come from another sector. Yet they present great opportunities for the power system. Innovations in technology, business models and regulation are necessary to tap the potential synergies between the two sectors.

This innovation outlook investigates the degree of complementarity potential between VRE and EVs and how this potential could be tapped with the implementation of smart charging by 2030 and 2050.

The report is organised into the following sections:

Section 2 summarises the state of play and provides an overview of current developments in the EV market as well as synergies with renewables.

Section 3 presents the outlook for smart charging, describing the different types of charging available today as well as projects in the field. It discusses how EV flexibility could evolve in both the medium (2030) and long (2050) terms. It also assesses the suitability of different types of charging infrastructure for smart charging, and the use of digitalisation as a smart charging enabler.

Section 4 assesses the EV market value chain and business models. It also takes stock of challenges and best practices for vehicle-grid integration (VGI).

Section 5 presents the outlook for e-mobility. It assesses the competitiveness of EVs compared to internal combustion engine (ICE) vehicles in terms of the total cost of ownership, and how this is expected to evolve. Battery technologies and evolutions in the transport system towards mobility as-a-service – and eventually towards widespread use of autonomous vehicles – are also described.

Section 6 discusses the impact of smart charging on the global energy system. It presents the results of modelling that has been conducted to assess the impacts of the key expected innovations in electromobility as well as on the EV-grid nexus.

Section 7 provides a concluding policy checklist that takes stock of the key insights of the innovation outlook as well as the quantitative modelling. It derives a list of the key steps for policy makers and other stakeholders that are necessary for deployment of the most promising innovations for maximising the synergies between EVs and renewable energy sources.

2. STATE OF PLAY

This section presents an overview of the current developments in the electric vehicle market and the regulatory incentives in place for light-duty vehicles (including passenger cars and light commercial vehicles of up to 35 tonnes), buses and trucks. It also outlines the key determinants of EV flexibility potential.

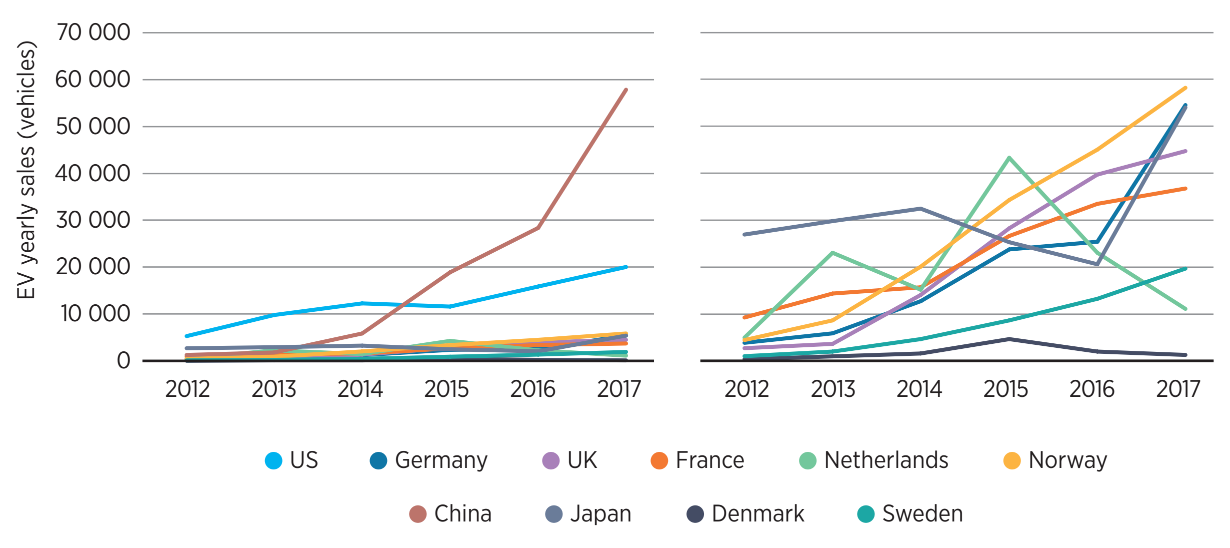
2.1 EV market evolution

According to the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), 5.6 million EVs were on the world's roads at the beginning of 2019. China and the United States (US) are the largest markets, with 2.6 million and 1.1 million EVs, respectively[2]. On average, EV sales grew rapidly during the period 2012 to 2017, with a compound annual growth rate (CAGR) of 57%. However, the market is still in an incipient phase, with EVs representing only 1.3% of all light-duty vehicles sold in 2017 (McKinsey, 2018). Policy support schemes and international, national and private commitments on EV deployment are the main drivers for the market uptake.

The Chinese EV market has experienced the largest increase in sales, with a CAGR of 114% between 2012 and 2017. In 2015 China surpassed the US in total EV sales, and in 2017 it was responsible for 48% of worldwide electric light-duty vehicle sales. The Chinese government has offered direct monetary incentives to support the purchase of EVs, including one-time subsidies and purchase tax exemptions, as well as non-monetary incentives, such as restrictions on registrations for ICE vehicles.

After China and the US, the next largest markets are in Europe, with considerable growth in EV sales from 2012 to 2017 in Germany (CAGR of 75%), Norway (70%) and the UK (68%). Figure 1 shows the evolution of EV sales in the 10 countries that represented 88% of worldwide electric light-duty vehicle sales in 2017.

Figure 1: Evolution of EV sales in the light-duty vehicle category in selected countries, 2012 to 2017 (charts including and excluding China and the US)



Based on Navigant Research, 2016c; BNEF, 2017a; ACEA, 2017; OICA, 2017.

---

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

Although the Chinese and US markets are the largest for EV sales, other countries have had greater success in integrating EVs into their overall vehicle fleets. Figure 2 shows the evolution of market penetration of EVs in light-duty vehicle sales. Norway has made remarkable progress since 2012, becoming a global leader with an almost 40% share of EVs in 2017. This was the result of a favourable policy environment in recent years comprising a large range of incentives, from tax breaks and exemptions to waivers on road tolls and ferry fees.

After Norway, the markets with the highest progress in EV integration between 2012 and 2017 were Sweden, the US and the Netherlands, with EV shares representing 5.1%, 3.3% and 2.7%, respectively, of the light-duty vehicle market in 2017. The remaining six largest markets did not exceed ratios of 2.5% of EV penetration and rank similarly to the global average. Note that the values provided for 2017 refer only to EV penetration in the passenger car category.

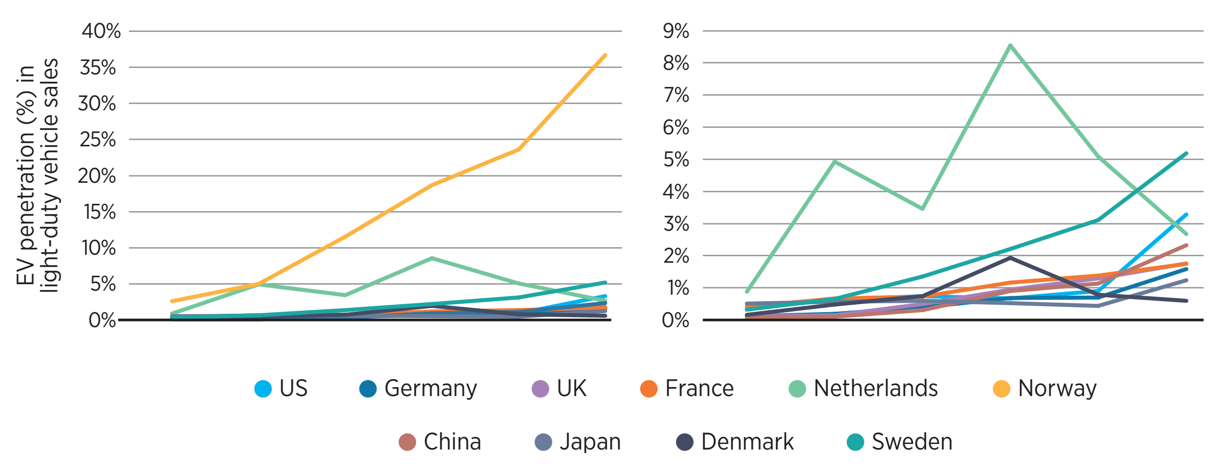
The arrival of total cost of ownership parity with ICE vehicles, the strong governmental support and the commitment to decarbonise the transport sector are key drivers that will boost EV adoption. Not only are private customers gradually shifting to EVs, but there is also an increasing trend in companies to turn their fleets "green" as part of ambitious emissions reduction plans or to capture attractive subsidies. These types of initiatives will represent a demand signal to the EV industry and will also encourage other business-to-business (B2B) customers towards similar activities.

The EV100 initiative, launched by The Climate Group in 2017, encourages companies to commit to moving towards 100% electric corporate fleets and to install charging infrastructure. In its first several months, the initiative had already signed on 10 multinationals, among them the Swedish power company Vattenfall, IKEA Group and the Chinese Internet giant Baidu (The Climate Group, 2017). Vattenfall has the most time-ambitious goal of the initiative so far, with the company setting targets to shift its fleets (3 500 light-duty vehicles) to 100% electric by 2022 as part of its goal to be climate neutral by 2050. The replacement will take five years and will include fleets in Germany, the Netherlands and Sweden (Vattenfall, 2017).

The French postal service La Poste is also a pioneer in the field, owning 35 000 EVs out of a total fleet of 75 000 vehicles (FleetEurope, 2017). In 2017 Germany's Deutsche Post DHL Group also set a target to achieve zero-emission logistics by 2050, in part through the use of EVs (see Box 1).

In addition to electrified conventional light-duty vehicles, a large market exists for other types of EVs such as buses and trucks. Table 1 shows the current market penetration of e-buses and e-trucks by region. As in the light-duty vehicle market, electric drive buses and trucks include plug-in hybrid EVs (PHEVs) and battery-only EVs (BEVs).

Figure 2: Evolution of the penetration of EVs in light-duty vehicle sales



Based on Navigant Research, 2016c; BNEF, 2017a; ACEA, 2017; OICA, 2017.

Box 1: DHL'S E-FLEET

In 2014 DHL acquired EV manufacturer StreetScooter. Thanks to an array of StreetScooter vehicles developed and manufactured in-house, as well as some 10 500 e-bikes and e-trikes, Deutsche Post DHL Group today operates the largest electric fleet in Germany. The company plans to replace its entire mail and parcel delivery fleet with EVs that are charged with electricity generated from renewable energy sources.

DHL's latest electric WORK delivery van, developed in partnership with Ford, has a 20.4 kilowatt-hour (kWh) battery and a range between 80 kilometres (km) and 200 km. It can carry a maximum of 700 kilograms of cargo. More than 2 500 of these vans were due to be in service by the end of 2018 (AirQualityNews.com, 2017).

DHL is now also selling the EVs – which have been designed for postal operations and for deliveries – to municipal authorities and other large fleet customers.

Table 1: Market penetration of e-bus and e-truck sales in 2016

Region	Buses	Trucks
North America	1%	0.3%
Western Europe	1%	0.9%
Eastern Europe	0%	0.2%
Asia Pacific	28%	0.2%
Latin America	0%	0.0%
Middle East & Africa	0%	0.0%
Total	**16%**	**0.2%**

Source: Navigant Research, 2016a; Navigant Research, 2016b.

The market for e-buses is concentrated mainly in Asia Pacific, where a market penetration of 27.6% was reached in 2016. Since 2014 there has been a large uptake of e-buses in China, which is now responsible for 99% of the worldwide sales and fleet. Market penetration in North America and Western Europe is around 0.6%. Whereas China reached 340 000 e-buses in 2017, the largest fleet of e-buses in Europe is in the UK and accounts for only 344 units (BNEF, 2018a). However, some segments such as school buses, for example in the US, have electrification potential that is increasingly attracting the attention of investors.

China is at the leading edge of the electrification of public transport buses because of the air pollution problems in its cities and industrial zones. The strategy of electrifying public transport comes from city administrations that want to reduce air pollution. The rapid and strong uptake of e-buses in Shenzen, for example, has helped to dramatically reduce the city's greenhouse gas emissions. The shift to e-buses is also supported by the national government, which has huge ambitions in mass transit. Apart from electrification, China has invested in a national high-speed railway network, subways and bus rapid transit.

In Europe, the number of e-buses is expected to grow considerably in the coming years. At least 19 public transport operators and municipalities in 25 European cities have outlined e-bus strategies for 2020 (UITP, 2016). Although the e-bus market is a small-production vehicle segment and is still in an early stage of development, it holds large growth potential for the near future due to increasing interest and the need of governments to decarbonise the transport sector.

The largest market for electric drive trucks is in Asia Pacific, responsible for around half of worldwide sales in 2016. However, electric trucks reached the highest market penetration in Western Europe. Although this is still a small market, with less than 10 000 units sold in 2016, the use of electric trucks is expected to rise rapidly in certain sectors such as smaller service and delivery trucks (IRENA, 2017a).

2.2 Policy incentives for EVs and charging infrastructure support

The current EV market penetration has been driven mainly by public (governmental) support for electric cars as well as for greater availability of charging infrastructure. Both monetary and non-monetary incentives contributed to the rise in EVs sales observed in the last five years. These incentives have been implemented at the national, regional and city levels.

In terms of monetary incentives, the Netherlands, Norway and Germany have implemented tax increases associated with the use of ICE vehicles and have provided tax benefits or exemptions to EVs. France, Germany and the UK have introduced one-time subsidies for EV purchases (EC JRC, 2017).

Non-monetary incentives can act as efficient alternatives to expensive subsidies. Countries such as the US and Norway allow EVs to use carpool lanes or bus lanes so that consumers can avoid traffic jams. The creation of low-emission zones to provide preferential access to low-emitting vehicles, as in some German cities and in the UK, is also an increasingly popular and powerful tool for cities to promote e-mobility. Nevertheless, such policies have only a temporary purpose of jumpstarting the e-mobility market. Keeping them in place permanently may have side effects, such as the crowding of carpool and bus lanes. Toll road charging also may need to be adjusted.

Some governments have set targets in the field of e-mobility. Table 2 provides an overview of key governmental e-mobility targets in the most relevant EV markets. The targets vary by country, not only in the level of ambition (*e.g.*, target year or absolute numbers), but also in how they are formulated. Reducing local air pollution is not the only motivation for these efforts; the Paris Agreement on climate change also plays a key role in driving countries' commitments to emissions reduction in the transport sector. The governments of France, the Netherlands, Norway, Spain and the UK have all set target dates for bans on the sale of fossil-fuel cars. These governmental targets complement carbon dioxide (CO_2) standards, such as those implemented in the European Union (EU) for new passenger cars and vans. By setting limits on the average CO_2 emissions of new passenger cars and vans, the EU aims to incentivise innovation and the supply of zero- and low-emission vehicles to the market.

In addition to vehicle fleets, some governments have set objectives related to the roll-out of charging infrastructure, as the lack of sufficient charging infrastructure represents a key barrier for EV sales.

Governments and public utilities around the world are incentivising the installation of charging stations at the residential level, in semi-public locations such as workplaces, and in public locations (see Box 2). Support for the development of charging infrastructure includes ambitious installations of charging points (also called electric vehicle supply equipment, or EVSE), targets and specific funding for implementation projects. Substantial support has been provided in China, several European countries and Japan.

For example, to roll out fast-charging networks Japan Development Bank is funding a consortium of four automakers and the utility TEPCO (Nippon Charge Service), and Chinese municipal governments are providing support in 88 pilot cities that have been co-operating with State Grid Corporation of China. In the US, partial government funding has been provided for charging infrastructure, and investor-owned utilities in California and several other states may seek approval to deploy EVSE that is ratepayer funded (*i.e.,* regulated), which requires review from utility regulators to ensure that such investments benefit all ratepayers and are not anti-competitive.[3]

Multinational forums of the world's key economies also play an important role in accelerating the energy transition towards clean mobility. Box 3 details the EV initiative of the Clean Energy Ministerial (CEM).

An overview of the various existing EV policy supports, comprising monetary as well as non-monetary incentives, and a number of case studies are provided in Annex 1.

---

[3] In Europe, the EV charging infrastructure cost must remain outside the regulated asset base of unbundled distribution system operators. Therefore, only commercial initiatives are possible.

Table 2: Key government targets and projections for e-mobility

COUNTRY	TARGETS
Austria	· 1.3% to 3.4% share of EVs on the road by 2020 · Between 3 500 and 4 700 publicly accessible charging points by 2020
Belgium	· 1.3% share of EVs on the road by 2020 · 8 300 publicly accessible charging points by 2020 · Ban on circulation of diesel cars in Brussels from 2030 (Manthey, 2018)
China	· 4% penetration of EV (PHEV and BEV) sales in the passenger car market by 2020 · In 2017 the country discussed a possible ban on the production and sale of diesel and petrol cars, to be implemented "in the near future" (Guardian, 2017).
France	· Ban on sales of fossil-fuel cars as of 2040
Germany	· 1 million EVs on the road by 2020 · 1 000 new EV charging stations on highways between 2017 and 2020
India	· Ban on sales of fossil-fuel cars as of 2030
Japan	· Increase the share of EV sales to between 20% and 30% by 2030
Netherlands	· Ban on sales of new petrol and diesel cars as of 2025
Norway	· All new passenger cars and vans sold in 2025 to be zero-emission vehicles
Republic of Korea	· 200 000 EVs by 2020
Spain	· Proposed law to ban sales of fossil-fuel cars by 2040 and their circulation by 2050 (Sauer and Stefanini, 2018)
UK	· Ban on sales of new petrol and diesel cars as of 2040 · 60% share of EV sales by 2030 and 100% by 2040 - 1.55 million EVs on the road by 2020
US	Although no clear national-level targets exists, many states and cities have set their own goals. For example: **Cities** · New York has a target of 20% EV sales penetration by 2025 and of an all-electric bus fleet by 2040 · Los Angeles aims to have a 10% share of EVs in the city by 2025 and 25% by 2035 **States** · California aims to reach 1.5 million zero-emission light-duty vehicles by 2025 and 5 million by 2030. It plans to spend USD 2.5 billion between 2018 and 2025 to expand the electric charging network infrastructure. · Illinois has targets for 60% PHEV sales and 15% EV sales by 2025 · In 2014 governors of eight states (California, Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island and Vermont) committed to collectively reach 3.3 million zero-emission vehicles on their roads by 2025, or 1.8 million excluding California

Based on EC, 2017; SLoCaT, 2017.

Box 2: CHARGING INFRASTRUCTURE INCENTIVES: CASE STUDIES

European Union (ICCT, 2016)
At the EU level, a directive on the deployment of alternative fuel infrastructure approved in 2014 asked Member States to outline implementation plans and targets for the installation of electric charging points, among other infrastructure. Also, from 2013 to 2015, under the EU's TEN-T programme, some EUR 35 million was invested in the installation of nearly 600 fast-charging stations along the main road networks of Northern Europe.

Ireland (Gallagher, 2018)
To support the government's goal of 30% penetration of zero-emission vehicle sales in the automotive market by 2030, a new measure was implemented in 2018 under which electric car owners can claim a grant of up to EUR 600 to cover the purchase and installation of residential charging points.

Amsterdam, The Netherlands (BNEF, 2017b)
In 2016 the city contracted with the energy utility Nuon to install public charging points. Under certain conditions EV owners are eligible to request the free installation of a public charging point. For example, EV owners should not have their own site or have access to private parking, and they should possess or be eligible for a parking permit at the requested address. In exchange, the Municipality of Amsterdam is allowed to use the data on charging, although anonymised, for research purposes.

UK (UK Government, 2016)
The Office of Low Emission Vehicles provides grant schemes to cover part of the cost associated with installing EV charging infrastructure. The funded amounts and the conditions depend on the end-users of the charging systems. The Electric Vehicle Homecharge Scheme provides residential customers grants that can cover up to 75% of the total procurement and installation costs. From July 2019, only home chargepoints that use 'smart' technology will be eligible for this government funding. Smart chargepoints are defined as chargepoints that can receive, understand and respond to signals sent by energy system operators or third parties to indicate when is a good time to charge or discharge in relation to overall energy supply and demand (RECC, 2019). A similar scheme is designed for local authorities that wish to install on-street residential charge points. Under the Working Charging Scheme, businesses, charities and public sector organisations can apply for a voucher of GBP 300 per socket up to a limit of 20.

California, US (Guinn, 2017)
California has the highest penetration of EVs in the US market. About 15 programmes implemented by the state government, utilities or municipalities incentivise the installation of charging stations. A specific cluster of customers (workplaces, multi-family houses, disadvantaged communities, businesses, municipal facilities, etc.) receives EVSE rebates or tax credits. For example:

- *Burbank Water and Power* offers customers that install a Level 2 (240 volt (V)) charging point a rebate of up to USD 500 (residential) and USD 1 000 (commercial). To be eligible for the rebate, applicants must be in the time-of-use electricity rate.
- The *Charge Ready* programme of Southern California Edison (SCE) creates partnerships between SCE, a regulated electric utility and local "site hosts" of EVSE. Site hosts commit to purchasing eligible EVSE at their own expense, and SCE installs, maintains and recovers costs from ratepayers for site preparation and distribution system upgrades.
- The *San Joaquin Air Pollution Control District*, under its *Charge Up!* programme, offers funding to public agencies and businesses in the region for the installation of public EV charging points. The applicants can receive up to USD 50 000 per year or up to USD 5 000 per unit.

Box 3: EV CAMPAIGN OF THE CLEAN ENERGY MINISTERIAL

An interesting example of multinational support for EV deployment is the recently approved EV30@30 campaign from the Clean Energy Ministerial (CEM) under the Electric Vehicles Initiative (EVI). The campaign aims to boost the e-mobility market – in terms of fleet adoption and infrastructure deployment – by setting a target of 30% EV sales by 2030. However, the target is applied collectively to the CEM-EVI members that have supported the initiative: the governments of Canada, China, Finland, France, India, Japan, Mexico, the Netherlands, Norway and Sweden.

The campaign also has obtained the support of the C40, the FIA Foundation, the Global Fuel Economy Initiative, the Natural Resources Defense Council, the Partnership on Sustainable, Low Carbon Transport (SLoCaT), The Climate Group, UN Environment, UN-Habitat and the International Zero Emission Vehicle Alliance (ZEV Alliance) (CEM-EVI, 2017).

The governments of France, the Netherlands, Norway, Spain and the UK already have announced timelines for bans on the sale of fossil-fuel cars. A number of countries have declared targets for e-mobility and for EV charging infrastructure and have implemented a wide range of monetary and non-monetary incentives.

2.3 Renewable energy share in the power mix in e-mobility markets

Electric vehicles have three main advantages for the transport sector: First, they run on a cheaper fuel, meaning that the per-km costs of electricity are typically lower than those for gasoline or diesel. Second, EVs emit no local pollution. They contribute to the reduction of particulate matter and noise emissions. Third, the energy efficiency of an electric powertrain is much higher than for an ICE powertrain. For an EV, the pump-to-wheels fuel consumption is about one-third to one-quarter that of an efficient ICE vehicle (EPRI, 2018).

EVs also generally emit fewer greenhouse gases than ICE vehicles, even if charged predominantly “with fossil fuels” (Creara, 2017). As shown in Figure 3, the relative CO_2 emissions from EVs depends on the grid supply mix. For example, in China EVs still emit less CO_2 on average than an ICE vehicle, whereas in India and Australia EVs emit more CO_2 on average than an ICE vehicle. By contrast, in Iceland, EVs are virtually non-emitting.

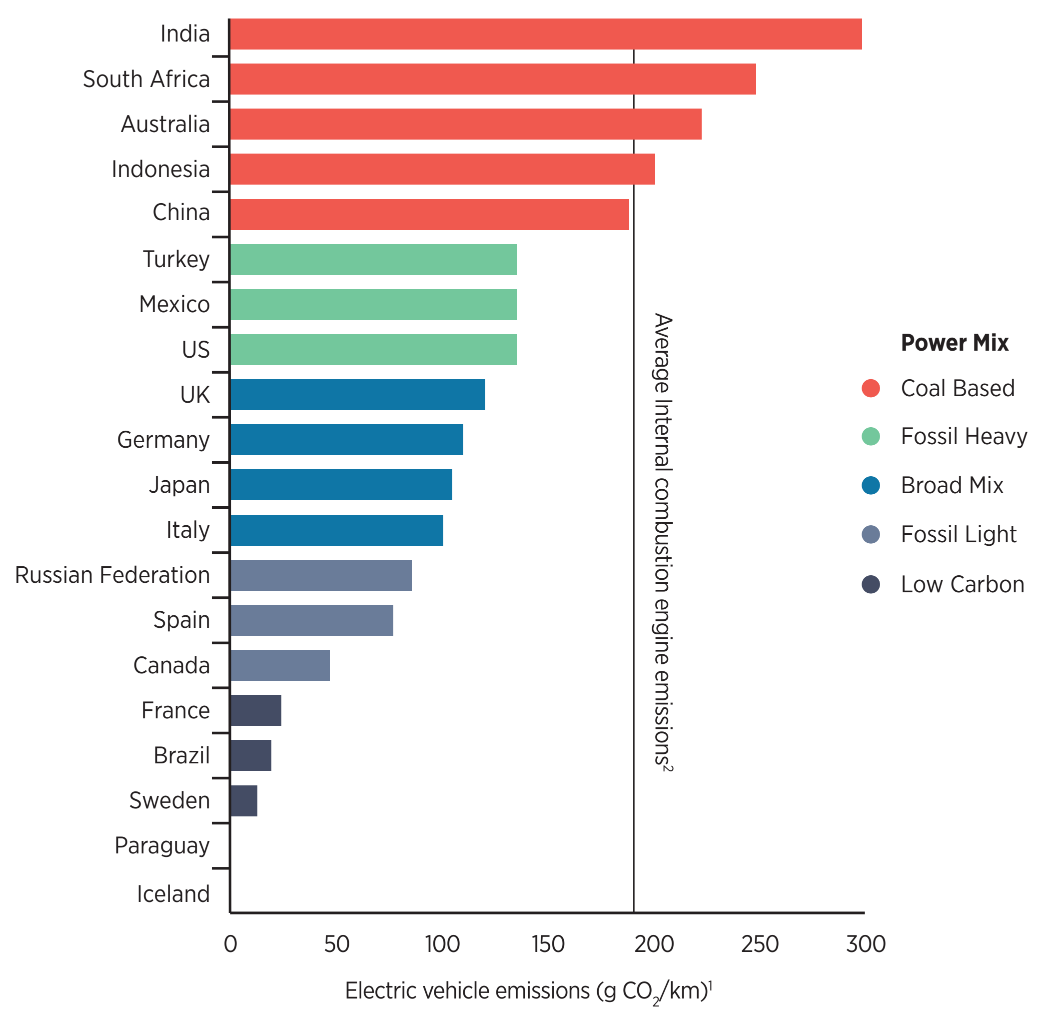
Even if EVs are not charged by electricity based on a renewable power mix, their immediate effect of reducing air pollution in cities – which causes millions of premature deaths each year – represents an important first step. The World Health Organization estimates that 9 out of 10 people in the world live in places where air contains high level of pollutants, and ambient air pollution accounts for an estimated 4.2 million deaths annually due to stroke, heart disease, lung cancer and chronic respiratory diseases (WHO, 2018).

However, to accomplish true decarbonisation of transport via electrification, the electricity used to charge the EV battery packs should be produced from renewable sources.

The potential to decarbonise transport through the use of EVs charged from renewable electricity is largely untapped due to low shares of renewables in the power mix of the countries with the highest numbers of EVs on the road, like the US. Similarly, countries with high shares of renewables can benefit from further electrification of transport. To reap the full benefits of both, electrification of transport needs to go hand in hand with decarbonisation of the power sector, not one without the other. The following figures explore how clean electricity can be used to charge the current EV fleet.

Figure 4 shows the total electricity demand in 2016, as well as an estimate of the total electricity consumption from light-duty vehicles (if all were electric). If all light-duty vehicles were electric in countries like the US, they would represent 24% of the total electricity demand. Given that the total amount of electricity produced from renewables in the US is around 18%, the power demand for all light-duty vehicles could not, even theoretically,

Figure 3: Carbon dioxide emissions of EVs



1 Results include direct grid emissions, indirect grid emissions and losse

2 GreenVehicleGuide, Australian Government

Source: Creara, 2017.

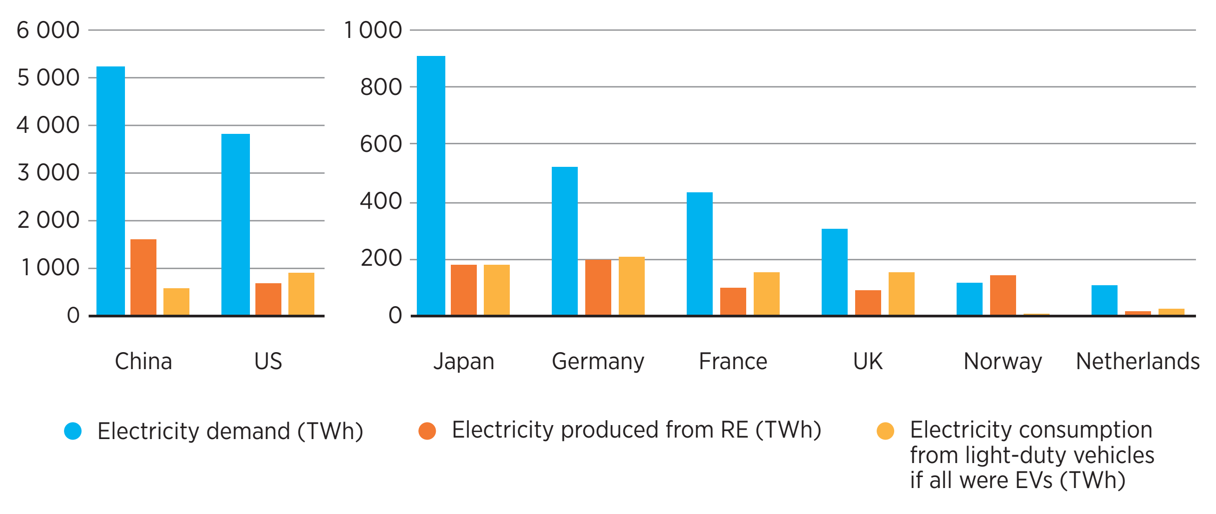
be met using "renewable electricity". This would also be the case in countries like Japan and Germany, among others, although to a lesser degree. This clearly signals the need to step up the decarbonisation efforts in these countries.

Figure 5 shows the relationship between three indicators in the same 10 countries analysed in Figure 1: EV penetration in the light-duty vehicle fleet, renewable energy share in electricity generation and current size of the EV fleet.

Norway is the country that is most likely to be able to supply clean power to charge a full-EV national fleet. Not only does close to 98% of the country's electricity generation come from renewable sources, but the total number of EVs in Norway is also limited in size compared to China and the US. Finally, the Norwegian energy mix is based on hydropower and thus is more flexible than power systems based on variable renewables like solar and wind. France's nuclear-based power mix, despite having a low share of renewables, is also predominantly low carbon.

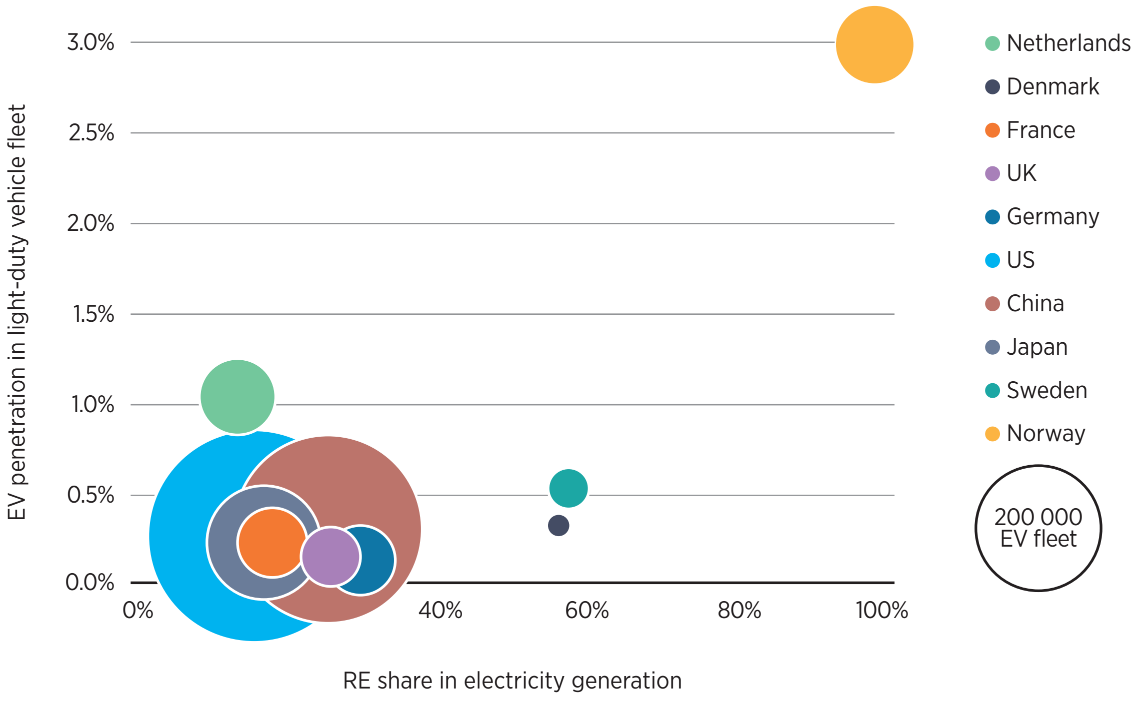
Charging EVs with renewable energy becomes more challenging when hydro generation is not available and variable solar and wind energy would need to supply the transport sector. While the countries with the highest numbers of EVs – China, France, Japan and the US – have a small share of wind and solar in their

Figure 4: Electricity demand, renewable electricity production and EV power demand in selected countries in 2016



Based on Enerdata, 2016; BNEF, 2017c; Tractebel, 2017.

Figure 5: Indicators of clean electric mobility penetration in selected countries in 2016



Based on Enerdata, 2016; Navigant Research, 2016c; ACEA, 2017.

generation mix, in Denmark and the Netherlands almost all the renewable electricity is generated by wind power. If only wind were used to supply the electricity demand from EVs, then Denmark – with 51% of its electricity generation coming from wind plants and an EV fleet limited in size – would be the country that is the closest to meeting EV power demand with wind (Figure 6).

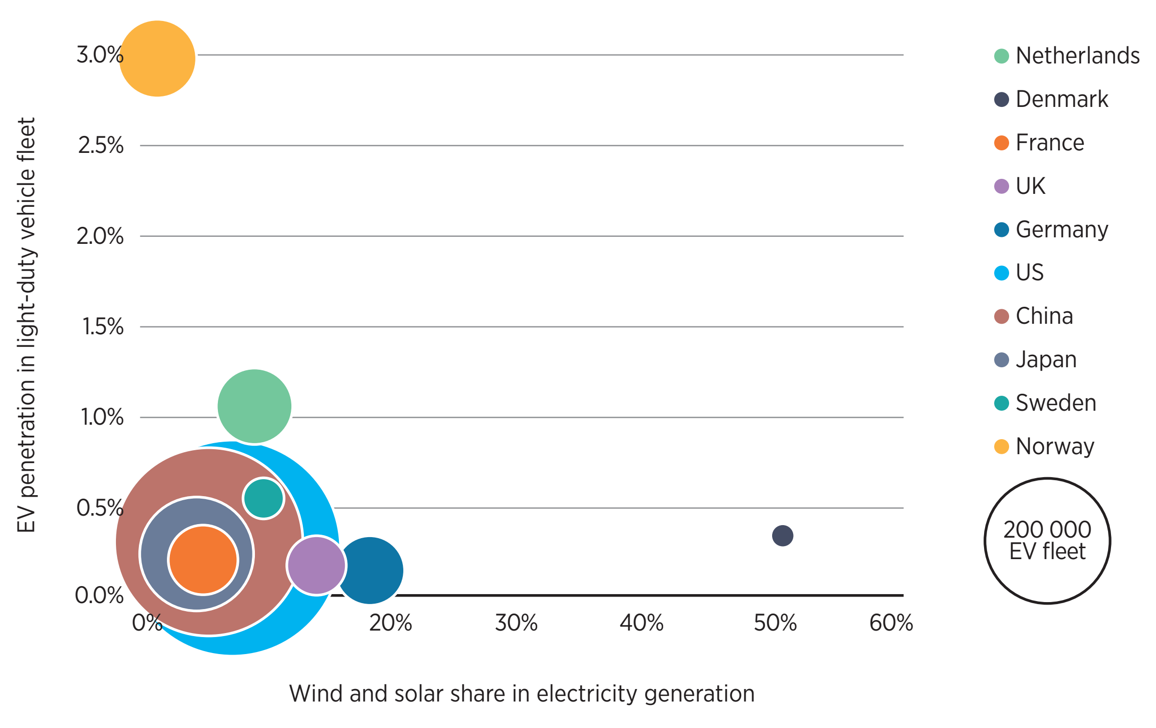
EV fleets can create a vast electric storage capacity to store the surplus production when renewable electricity generation exceeds demand. However, the most optimal charging patterns will depend on the renewable mix. EV integration strategies in the power system are very different in a system with high shares of solar generation then in a system where wind generation prevails.

Figure 7 and Figure 8 highlight the wind and solar share in electricity generation separately. The examples of Japan and Sweden are worth noting. While Sweden's entire VRE generation comes from wind, Japan´s comes from solar. In this sense, Japan could use its 26 GW of pumped storage hydro to store excess solar PV during the day, and then use that electricity to charge the EVs at night. However, in the Swedish case, charging of EVs could be more spread throughout the day and night to match the availability profiles of wind.

The type of VRE electricity share, driving patterns and charging needs are three variables that need to be considered together when maximising the synergies between EVs and VRE, and the decarbonisation of the transport fleet. More in-depth insights about the impact of EV integration into high-solar or high-wind isolated systems are presented in section 6.

While EVs do not release emissions when driven, they use electricity that often still comes largely from fossil fuels. To reap the full benefits of both, electrification of transport must go hand in hand with decarbonisation of the power sector.

Figure 6: EV penetration in light-duty vehicle fleet compared to share of wind and solar in electricity generation in selected countries in 2016



Based on Enerdata, 2016; Navigant Research, 2016c; ACEA, 2017.

Figure 7: EV penetration in light-duty vehicle fleet compared to share of wind in electricity generation in selected countries in 2016

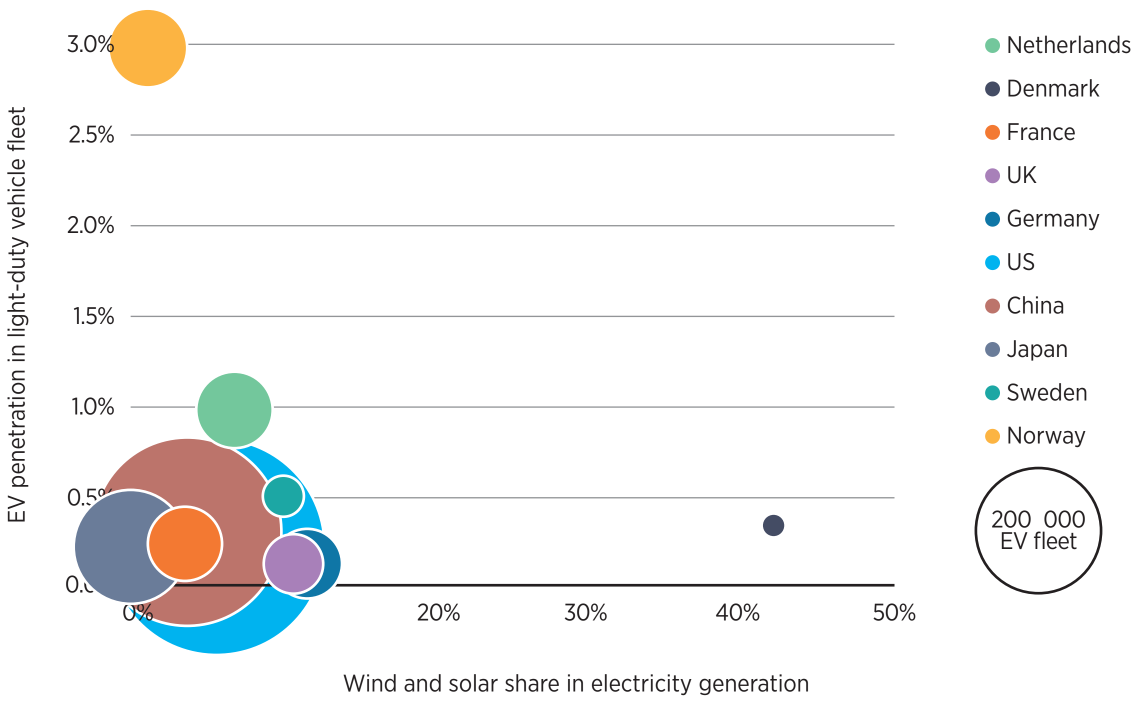
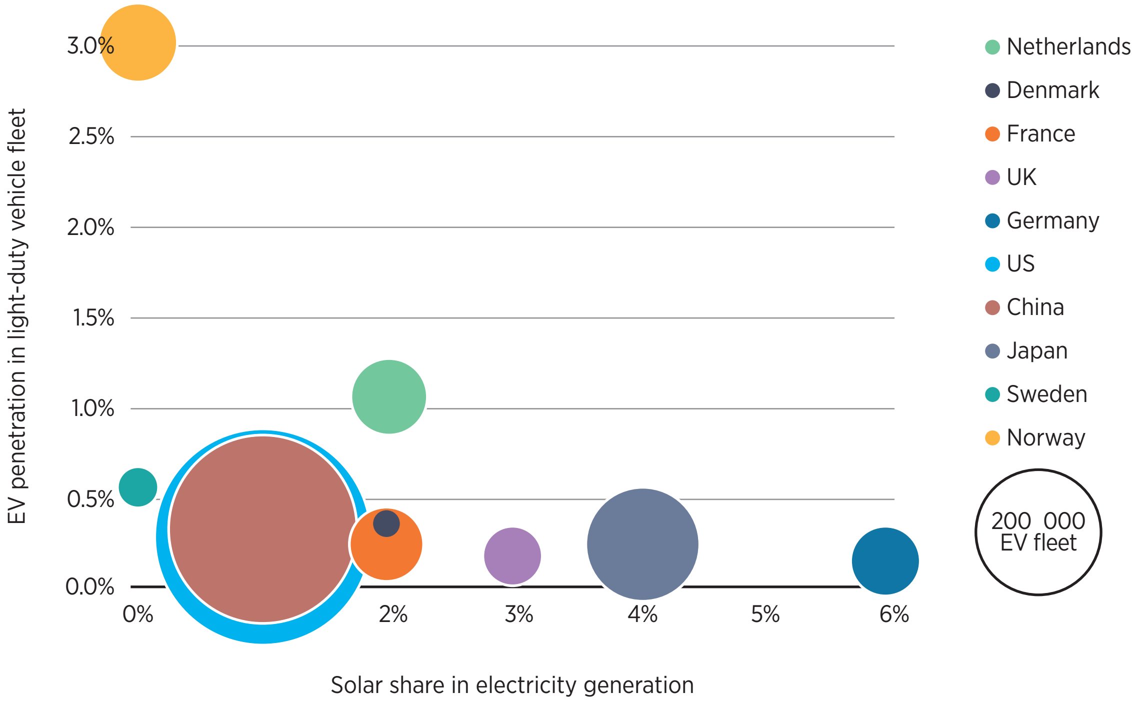


Figure 8: EV penetration in light-duty vehicle fleet compared to share of solar in electricity generation in selected countries in 2016



Based on Enerdata, 2016; Navigant Research, 2016c; ACEA, 2017.

2.4 EV flexibility potential

The uptake of smart charging for electric mobility is expected to establish a positive feedback loop with the integration of renewables, given that e-mobility is a power-dense, mobile and controllable load. Studies have shown that cars in general, including EVs, are parked for about 95% of their lifetime (Pasaoglu *et al.*, 2012). This, combined with their storage capacity, could make EVs an attractive flexibility solution to support system operation. They can become grid-connected storage units with a potential to provide a broad range of services to the system. 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).

The typical electricity consumption of an EV driving 15 000 km/year is about 3 000 kWh/year. Even with slow charging (*i.e.*, charging with low power, say 3.7 kW), the total time needed to charge the yearly energy is about 10% of the time the car stands idle. Supposing that an EV is connected to charging infrastructure 100% of its parking time, this means that the yearly "flexibility window" for charging represents about 85% of the time. Theoretically, this would translate into a flexible energy output of about 3 000 kWh/year per car. In other words, EVs can be charged in a fraction of their parking time. Incentivising charging at times when electricity is the cheapest represents a significant opportunity for the power system and for EV owners.

In practice, flexibility can be lower due to drivers' time constraints, with fast charging, or when the vehicle is parked but not plugged in. The different factors that determine the amount of available flexible (dis-)charging energy from EVs available in the system are summarised in Figure 9.

EVs providing power system flexibility today

Today, the EV fleet is very limited and the cars still have relatively small batteries. EVs can already help maximise self-consumption of on-site renewable production. However, the flexibility that EVs provide to the grid is limited. Their aggregated storage capacity today is marginal from a power system perspective.

How long the car can be connected to the grid depends on the immobilisation time, which is determined by the type of vehicle and its use. Taxis or buses that travel a high daily distance will have less immobilisation time and therefore less flexibility than single cars used by individuals. While an electric bus or truck may use 100% or more of battery capacity every day, passenger cars and two-wheelers may use 40% to 50% of it (Ghatikar *et al.*, 2017).

When and where the vehicle is charged also depends on the car type, its use, the geography and the availability of the infrastructure:

- *Individual electric cars* have predicTable charging patterns:

Figure 9: Factors determining the amount of available flexibility from a single EV

HOW LONG: Standing idle and "plugged in"	**WHEN: Time of day**	**WHERE: Charging location**	**WHAT: Charging technology/ power level**	**HOW MUCH: Battery capacity and desired state of charge at departure**
• Personal vehicles • Taxis • Buses	• Day • Evening • Night	• Home • Office • Highway • Destination locations (recreation facilities, retail centres...)	• Slow • Fast • V2X equipped	• Entry BEVs • Premium BEVs • Buses

  - Long-duration (> 4 hours) charging provides the highest flexibility for the system: most of the charging takes place at home during the evening, and at night and at the workplace during the day. EV drivers without home charging need assigned workplace charging.
  - Medium-duration (30 minutes to 2 hours) charging at shopping or leisure centres (movie theatre, gym, etc.) or short-duration (15 minutes to 1 hour) charging provide minimum flexibility for the system and are ill-suited for grid services: fast charging on highways is rather exceptional today as EVs are mostly not yet used for long trips (due mainly to the limited range issue and the lack of appropriate charging infrastructure).

- Charging patterns of *shared and commercial cars* (*e.g.*, taxi and other car fleets) may be less predictable, depending on the business models. Nevertheless, the transport service revenue is critical and the time of standing still should be reduced to a minimum, leading to smaller time with grid connection and higher charging power, compared to individual cars. While cargo transport may occur mainly during the night, commercial services like taxis still have higher demand during the day.

- *Electric bus* charging patterns depend on the place of charging:

  - Long duration (> 4 hours) at the bus depot
  - Medium duration (10 minutes) at the bus end-of-line
  - Very short duration (flash charging) (30 seconds) at the bus stop.

Interaction with the vehicle owner is key, including the forecasting of use in terms of schedule and driving distance.

Depending on the geography and specifically the access to a private parking space at the residential level, the proportions among the charging locations might differ. In less densely populated areas, most of the charging cycles are performed at home or at work. In densely populated cities with no charging points at home or at work, a larger proportion of the charging could be done in public places in the city. Large parking spaces or bus depots have more technical opportunities and incentives to contribute to energy flexibility than do disperse charging locations. However, most charging is done at home and at the office today due to individual ownership of vehicles and to the low cost of charging this way. That determines what charging infrastructure is used:

- Today, most chargers are slow chargers installed at private and semi-public premises. Having assumed that each car has mainly a private charger available, the International Energy Agency estimated that private chargers outnumbered public charging stations by more than six to one in 2016. However, fast-charging installations have been growing at a higher rate than slow charging in the last few years (IEA, 2017).

- Today, charging stations and cars may not yet be equipped for smart charging. Not all technical preconditions, including the ability of charging stations and vehicles to communicate with each other and provide flexible power by discharging, are fully developed.

How much battery capacity can be made available for smart charging depends on the vehicle's battery capacity and on drivers' needs:

- The battery capacity: electric 2-3 wheelers will offer less energy flexibility than premium cars with bigger batteries. A few orders of magnitude are given as follows (EAFO, 2017):

  - Entry BEVs: 20-40 kWh in 2017 (*e.g.*, Renault Zoe, Nissan LEAF), 40-60 kWh in 2018-2019 (*e.g.*, Renault Zoe, Nissan LEAF, VW eGolf)
  - Premium BEVs: 60-100 kWh in 2017-2018 (*e.g.*, Tesla Model S)
  - PHEV cars: about 8-16 kWh
  - BEV buses in 2017: 100-400 kWh (some models up to 600 kWh)
  - E-motorcycles: typically 3-20 kWh
  - E-bikes: typically 500 Wh.

- Sufficient state of charge – *i.e.*, the available capacity of the battery at time of departure – should be guaranteed. At the moment of disconnection, the battery should have a state of charge that meets the driver's requested range (typically at 70-80%) so that the car can still provide sufficient range. However, the importance of this parameter will decrease with EVs having larger batteries, and with higher penetration levels for charging stations.

- The capacity that an EV can provide for flexibility services will increase if the EV is V2X-enabled (*e.g.*, about three to four times as compared to V1X). Increased maintenance, reduced efficiency and impact on the battery lifetime due to charging and discharging patterns (guarantee, range anxiety, etc.) also need to be further evaluated before massive deployment, as these questions remain despite several positive test results (De Vroey, 2016) (see Annex 2).

EVs providing power system flexibility by 2030

In the future, the availability of flexibility will greatly increase with the number of EVs on the roads, but it also will be affected by developments on the power system side and by mobility trends, as depicted in Figure 11 and Table 3.

By 2030 individual ownership of vehicles will most likely still prevail over car sharing. As a result, an increase in flexibility can be expected:

- More EVs available to the grid due to falling cost: EVs get cheaper due to falling battery cost and government policies, as outlined in the previous section.

- Bigger batteries helping to overcome range anxiety: there will be more EVs with larger batteries connected to the grid. Battery packs will be bigger – increasing from 20-30 kWh currently to 40-60 kWh, with ranges of around 300 km becoming widespread in the next two years and growing even further.

- Cars, charging stations and smart charging and discharging functionalities: as standardisation progresses and as the requirements for better control of the charging power increase, the vehicles and charging points will have smart charging options including discharging as a common feature (provided by auto manufacturers), and technically enabling provision of ancillary services to the grid. A series-produced EV with alternating current (AC) charging and vehicle-to-grid (V2G) capability would greatly lower the entry cost to customers (Kempton, 2016).

- More opportunities for EV drivers to charge at workplaces.

Fast charging will remain limited as drivers will use it mainly for long-distance trips and for necessary top-ups given that enough range is available and as long as charging at home remains cheaper. While higher nominal charging capacity generally increases the challenge of uncontrolled charging, daytime fast charging could be aligned with grid needs in areas with high solar production during the day.

EVs providing power system flexibility by 2050

Between 2030 and 2050, this picture could change substantially. Mobility business models such as mobility-as-a-service (MaaS) – *i.e.*, seamless multimodal transport – and technologies such as autonomous vehicles may emerge and be broadly implemented, leading to a shift from individual ownership of vehicles to fleet management.

Studies have shown that “ride-sharing” could lead to an increase in the number of kilometres driven as the shift from public transport towards shared private transport occurs at a larger scale. However, it also should lead to lower use of private cars with low passenger occupancy, which could in turn imply a reduction in the net emissions of the transport system (Santi, 2017).

Nevertheless, downwards pressure on available flexibility is likely to occur under this scenario, as:

- Distance travelled by individual cars would increase, reducing the amount of time that they are idle, connected to the grid.

- MaaS will also eventually impact the number of EVs in the system. The increase in EV sales would slow down: under the assumption that the EV revolution will precede the advent of an advanced MaaS ecosystem, new business models in MaaS will translate to downwards pressure on car sales for individuals after approximately 2030, following years of increasing market growth.

- Zones of strain on the local power grid can be created once charging is focused in hubs. These hubs may be relevant for centralised flexibility management in the night but still probably lower than with individual car ownership, as transport service optimisation will aim at maximum usage. Vehicle fleets will have to be steered towards an optimised fleet charging and routing, contributing to the goals of EV grid integration and optimised renewable energy use.

Figure 10 summarises the status of EV flexibility for 2030 and 2050.

Impacts of this trend will be notably relevant in urban areas – where 60% of the world population is expected to live by 2030 and 70-80% by 2050 (Demographia, 2017) – due to the major increases in urbanisation in densely populated cities in emerging economies. The uptake of MaaS and fully autonomous driving will also depend on the city structure. Outside urban areas the individual ownership model will still prevail, with EVs increasing flexibility in remote locations.

The availability of infrastructure and enabling regulation will highly impact the speed of uptake of fully autonomous vehicles. For these reasons, massive penetration of these vehicles is not expected before 2030s (and in most locations perhaps later), even though reliable technology may be available much before.

Figure 11 illustrates the different trajectories of flexibility evolution. The two shades of blue indicate two possible scenarios of autonomous vehicle adoption:

- In the first scenario (marked in light blue), autonomous vehicles come early and flexibility from single EVs flattens out already before 2040.

- In the second scenario (marked in dark blue), autonomous vehicles continue to spread until 2040, before dropping.

Changes in vehicle ownership and use will alter driving patterns and charging requirements. Charging requirements will still principally determine available flexibility for the grid.

Figure 10: Evolution of EV flexibility for renewable energy integration by 2030 and 2050

	Today	2030	2050
🚗	🔴 Low penetration	🟢 High penetration	🟢 High penetration
🔋	🔴 Small batteries (30-60kWh) → Low driving range (150-300km)	🟢 Large batteries (90-200kWh) → High driving range (600-1000km) (?)	🟢 Large batteries (90-200kWh) → High driving range (600-1000km)
P	🟢 Standing still 90% of time	🟢 Still high parking time	🟠 Reduced parking time
⛽	🟢 Home & office charging	🟢 Still mostly home & office charging	🟠 Hubs in city suburbs (mostly night)
💡	🔴 Smart charging in testing phase Only ToU more common	🟢 Smart charging implemented, market-dependent potential	🟢 Smart charging implemented, market-dependent potential

🟢 *Positive for EV flexibility* 🔴 *Negative for EV flexibility* 🟠 *Less positive impact than in 2030*

Figure 11: Illustrative outlook of available flexibility from a single electric light-density vehicle in urban context

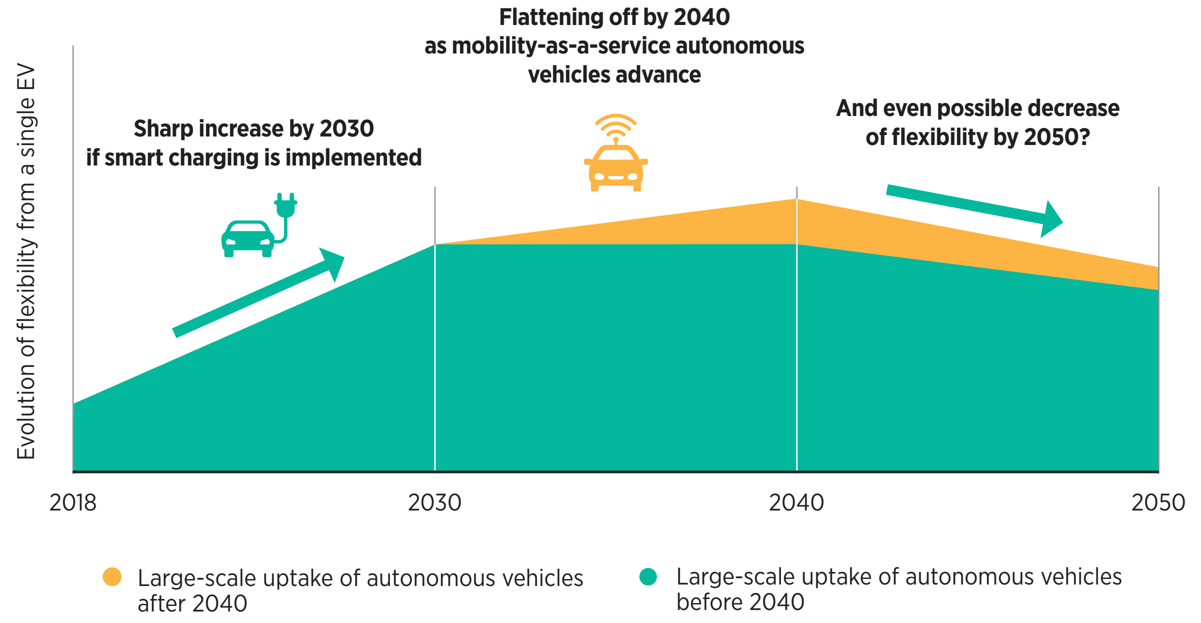


Table 3: Impact of mobility evolution on flexibility parameters in 2030 and 2050

	2030: **EV with large batteries + smart grid + individual ownership**	**2050 in urban areas:** **EV with large batteries + smart grid + MaaS and autonomous vehicles**
WHEN: **Time of day**	Partly day, mostly night	Mostly night
WHERE: **Charging location**	Still mostly home (residential neighbourhoods) and workplace (business districts)	Hubs in city suburbs
WHAT: **Charging technology/power level**	Mostly slow; fast to “top-up”	Slow in hubs during the night; fast to “top-up”
HOW MUCH: **Battery capacity and desired state of charge at departure**	Increased battery capacity; no need to fully top off	Increased battery capacity; may need higher top-off to minimise stops
HOW LONG: **Standing idle**	Still most of the day	Minimum time for day charging; longer at night (depending on the type of transport service)

3. SMART CHARGING OUTLOOK

This section reviews the different smart charging approaches and the status of smart charging infrastructure and provides an outlook based on the lessons learned from existing pilot projects and research in the field.

3.1 Impact of charging EVs

Impact on electricity capacity and demand

If EVs were charged simultaneously in an uncontrolled way they could increase the peak demand on the grid, contributing to overloading and the need for upgrades at the distribution level. The extra load may even result in the need for upgrades in the generation capacity (or at least in an altered production cost profile). The extent of possible impacts would depend on the power system's electricity mix, grid typology and penetration of EVs, as demonstrated by various trials and studies conducted globally.

The studies converge on three main conclusions about the impacts of EVs on the power system and how these impacts can be mitigated:

1. Impact on electricity demand will be limited:
   - In a 100% electric mobility scenario for Europe, the energy needs of EVs might represent no more than 10% to 15% of total electricity production. However, EV grid integration might lead to local power issues with increasing EV volumes (Eurelectric, 2015).
   - If all 2.7 million cars in Norway were EVs, they would only use 5-6% of the country's annual hydropower output (BoA/ML, 2018a).
   - In a 25% electric mobility scenario for Germany, 10 million EVs by 2035 would translate to an overall consumption increase of only 2.5-3% (Schucht, 2017).
   - If all light-duty vehicles in the US were electric, they would have represented about 24% of the total electricity demand in the country in 2016, as shown in section 2.3.

2. The impact on peak demand, however, can be much greater if the additional demand is not distributed smartly. For this, smart charging is key:
   - In a 10 million EV scenario for the UK by 2035, evening peak demand increases by 3 GW if charging is uncontrolled, but increases by only 0.5 GW if charging is smart. With smart EV charging, the lowest price periods could see demand increase by 7 GW (AER, 2018).
   - Modelling of EVs in New England showed that a 25% share of EVs in the system charged in an uncontrolled fashion would increase peak demand by 19%, requiring significant investment in grid and generation capacities. However, by spreading the load over the evening hours, the increase in peak demand could be cut to between 0% and 6%. And charging only at off-peak hours could avoid any increase at all in peak demand (RMI, 2016).

3. The impact on local distribution grids might also be significant if not managed with smart charging:
   - Xcel Energy, Colorado in the US demonstrated that 4% of distribution transformers could be overloaded at EV market penetration of 5% if charging is aligned with peak load times (Xcel Energy, 2015).
   - The My Electric Avenue Project in the UK identified a need for 32% of distribution circuit upgrades with a 40-70% share of electrified cars (EA Technology, 2016).
   - In Germany, "dumb" charging of EVs under a 10 million EVs by 2035 scenario would lead to a 50% increase in low-voltage grid and transformer costs, while optimised peak shaving using smart charging would avoid these investments (Schucht, 2017).

Impact on grid infrastructure

EV charging will have an impact on distribution grid investments. The scope of grid investments (in terms of cables and transformers) that will need to be made in a given location will depend at least on the following parameters:

- **Congestion:** such as in the local distribution network prior to any EV deployment.

- **Simultaneity factor:** as applied based on the size of each distribution grid. The simultaneity factor/co-efficient measures the probability that a particular piece of equipment will need to be switched on at the same time as another piece of equipment. Every distribution system operator considers a different simultaneity factor.

- **Load characteristics:** for example, the impact of uncontrolled EV charging will be higher in locations with high shares of electric heating (thus leading to higher grid reinforcement). But if smart charging is used in such locations, it may be included with lower grid reinforcements than in locations where no electric heating is used, as the local grids are dimensioned for higher peaks.

- **Generation assets connected at low voltage level:** for example, integration of high shares of solar PV connected at low voltage level (*e.g.*, in Germany) could be facilitated with smart charging, whereas in locations with no or very low shares of solar PV, EVs could increase the strain on local grids.

- **Grid code limits and other regulations:** for example, national grid codes define physical constraints in terms of both voltage and frequency variations that distribution system operators have to respect, and investment in grid reinforcement if these country-specific limits are exceeded due to EV charging**.**

The case study of the city of Hamburg, Germany in Box 4 quantifies the impact of EVs in terms of possible bottlenecks and describes the distribution system operator's strategy to tackle those.

Fast charging represents a challenge for grid infrastructure development. The higher the power, the more capacity you need from the distribution grid. In addition, the locally deployed charging station/cables and vehicle must support this power. Both of those are technologically feasible but come at a price:

- Vehicles require more expensive electronics and protection devices.

- Grid connection of fast-charging stations requires bigger cables and transformers.

- Such charging stations require more expensive electronics and cooling as well as protecting devices.

- Active cooling of the charging cable is needed if very heavy cables are to be avoided. Increasing voltage from today's level will mitigate the need for heavier cable and/or active cooling, but this is not an optimal solution considering the interoperability with the existing infrastructure (and with the existing EVs). During the transition, cars may implement both technologies for compatibility. For example, Porsche is working on an 800 V capability Taycan model that is downwards compatible with the currently deployed 400 V charging stations (Porsche, 2016).

- Finally, the charging power for EVs is not only related to individual users' needs. For example, charging stations on highways implement several charging points whose power demand will increase with the increasing volume of EVs.

Table 4 provides an indicative example of a highway charging station, in comparison with a classical petrol station. A 6 MW capacity would be a good order of magnitude for a highway station with 30 charging points, in the medium term. This is the nominal power of a large windmill today. Moreover, 6 MW is also the power that would be needed by an electric car to charge energy at the same speed as a conventional ICE car (*e.g.*, typically 100 km charged in 15 seconds).[4] This is neither economically viable nor realistic with the current and medium-term battery technologies. In addition, this theoretical need would be in practice counterbalanced by the decreasing consumption of the new EV models.

---

[4] One litre of diesel is about 10 kWh. That means that for a car tank of 50 litres, 500 kWh is needed. If the charging time is to be equivalent to filling a tank (about five minutes), this equals about 6 MW (500*12). A charging curve does not maintain constant power: at the end of the cycle, the power decreases. Thus, a certain average power level (like 4.8 MW) requires a higher level (like 6 MW) at the beginning of the charging cycle.

Box 4: EV CHARGING IMPACT ON HAMBURG'S DISTRIBUTION GRID

Hamburg is currently the city with the highest number of charging points in Germany (several hundred charging points in households and 810 public charging points as of November 2018). The city expected to install 1 000 public charging points by the beginning of 2019. Electrification of public buses and EV growth are the most critical drivers of load development in the city. The majority of EVs will be in the suburbs where, in Hamburg's case, the grid is weaker (Pfarrherr, 2018).

The local distribution system operator, Stromnetz Hamburg, ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point loads of 11 kW and 22 kW. A 9% EV share, corresponding to 60 000 EVs loading in private infrastructure, will cause bottlenecks in 15% of the feeders in the city's distribution network (Pfarrherr, 2018).

To avoid these critical situations, Stromnetz Hamburg assessed that investment needs for reinforcing the local grids would reach at least EUR 20 million. Stromnetz Hamburg is also exploring alternative solutions to address the problem. The key is to decrease the simultaneity, meaning decreasing the number of EVs that are charged at the same time on the same local grid. For that, a smart solution using digital technologies is being tested, which includes a real-time communication system that enables the distribution system operator to reduce the load of the charging points needed to address the problem. The 11 kW charging points, for example, can reduce their load from 16 amperes (A) to 8 A, allowing EVs to be charged but in a longer period of time.

For this project, Stromnetz Hamburg partnered with Siemens, which will install 30 control units and monitor the private charging infrastructure loads. This will help them anticipate congestion issues and plan the network based on the load profiles. The estimated cost of this solution is around EUR 2 million, which is just 10% of the cost of reinforcing the cables in a conventional solution.

The case of Hamburg shows not only the impact that EVs may have on local grids, but the potential solutions to address it that may require a combination of digital technologies, new business models and market regulation to engage all the needed actors. (see also Section 6.2)

Table 4: Comparison of highway charging station with a classical petrol station

Highway tankink station, conventional cars	Highway tankink station, elec cars
2 minutes for 1 tanking cycle	20 minutes for 1 charging cycle
800 km tanked per cycle	400 km charged per cycle
E.g., 30 tanking points	30 charging points[1] = 6 MW

1 Could be much more to take into account the higher time needed for charging, but counterbalanced by limited EV volumes

3.2 Smart charging

Role of smart charging

Services provided by smartly charged EVs

Smart charging using vehicle-grid integration (VGI) technologies is a means of managing EV loads. This is done either by customers responding to price signals, by the EVSE automated response to control signals that react to the grid and market situations, or by a combination of the two while respecting customers' needs for vehicle availability. It consists of shifting some charging cycles in time or modulating the power in function of constraints (*e.g.*, connection capacity, user needs, real-time local energy production). Smart charging therefore is a way of optimising the charging process according to distribution grid constraints and local renewable energy availability, as well as the preferences of drivers and EVSE site hosts.

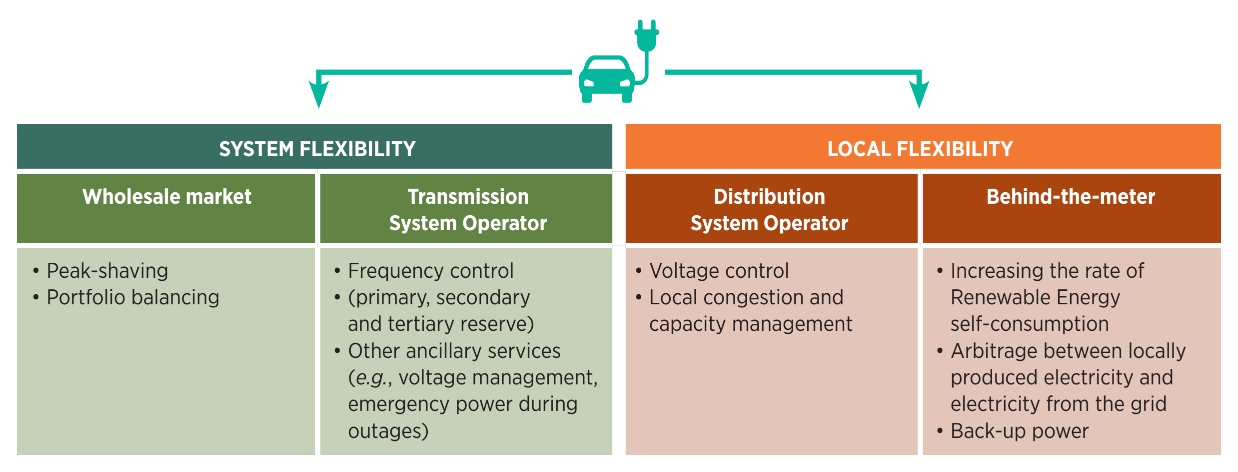
If charged smartly, EVs can not only avoid adding stress to the local grid but also provide services to fill flexibility gaps both on the local level and on the system level (Figure 12). Smartly (dis-)charged EVs could help reduce VRE curtailment, improve local consumption of VRE production and avoid investment in peaking generation capacity, as well as mitigate grid reinforcement needs.

The EVs can operate as grid-connected storage units with a potential to provide a broad range of services to the system. They could alternate their charging patterns to flatten peak demand, fill load valleys and support real-time balancing of grids by adjusting their charging levels. Quantitative modelling of isolated VRE-based systems – the main focus of section 6 – illustrates the possible range of synergies in more detail. The section also includes illustrative case studies of mitigating local distribution grid impacts.

Smart charging not only mitigates EV-caused demand peaks but also flattens the load curve to better integrate VRE, both at the system level and locally, at the shorter-term time scales. More specifically, adjusting charging patterns that today stand idle in parking for most of the time (90-95% of the time for most cars) could contribute to:

- *Peak shaving* (system level/wholesale): flattening the peak demand and filling the "valley" of demand by incentivising late morning/ afternoon charging in systems with large penetration of solar and night-time charging that could be adjusted following night-time wind production as cars are parked for longer time than they need to fully charge. Early-evening charging that may otherwise increase peak demand would be deferred in this way.

Figure 12: 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

EVs can contribute to decarbonising the transport sector while facilitating the integration of VRE. If EV charging is adjusted to follow the availability of renewable energy sources, less flexibility from conventional power plants will be needed.

- *Ancillary services* (system and local levels / transmission and distribution system operators): supporting real-time balancing of grids by adjusting the EV charging levels to maintain steady voltage and frequency. While flexibility has been well-developed at the system level by transmission system operators, distribution system operators are mostly not yet equipped with flexibility from distributed energy resources for operating their grids, despite the high number of demonstration projects that have been conducted and intense regulatory discussions in several countries (mainly in Europe and the US).

- *Behind-the-meter* optimisation and *"back-up power"* (local level / consumers and prosumers): this includes increasing self-consumption of locally produced renewable electricity as well as lowering dependence on the electricity grid and reducing the energy bill by buying cheap electricity from the grid at off-peak hours and using it to supply home when the electricity tariff is higher (during evenings).

Concrete services controlled by grid operators are listed in Annex 2.

Batteries capabilities to provide grid services

EV battery capacity and technical characteristics determine the extent to which cars support renewable power integration. Today, most EVs rely on some type of lithium-ion based battery. Cost reductions coupled with battery performance improvements and suitability for grid applications make this technology a worthy choice.

EV batteries' capabilities to provide specific grid services are key in this context, setting aside their impact on the vehicle's performance. Capabilities to provide services to the grid and corresponding technologies will depend on the considered application.

For example, for balancing renewables, high depth of discharge tolerance, *i.e.*, the extent to which the battery can be discharged, is necessary. Three hundred full cycles per year may be required if the battery is to be used to support system-wide balancing or absorption of excess renewables into the battery behind-the-meter. For ancillary services, lower depth of discharge is required. Since batteries must both be able to inject power (when frequency is too low) and consume power (when frequency is too high), the ideal standby state of charge is approximately 50%, which means that the selected batteries should be able to work at lower states of charge.

Key technical terms for classifying battery technologies:

- **End of life** (EoL): moment when the battery retains only a fraction (typically 70%) of its initial capacity. It is expressed as a percentage of initial capacity.
- **Depth of discharge** (DoD): the percentage (compared to full capacity) to which the battery can be discharged.
- **State of charge** (SoC): the capacity of the battery expressed as a percentage of the full capacity at which the battery is during usage charge.
- **Cycling rate** (C-rate): the rate of charge or discharge. 1C refers to a charge or discharge in 1 hour, 2C refers to 2 hours, and 0.5C refers to 30 minutes.

Today, lithium-ion (Li-ion) is the prevalent EV battery technology. The comparison of different batteries used in mobility with other stationary batteries in Table 5 demonstrates that Li-ion can compete with other technologies used for stationary storage such as lead acid and redox flow (IRENA, 2017b). Today Li-ion remains the most mature technology for a broad range of grid services, as detailed in Annex 2.

Battery degradation from increasing the number of charge/discharge cycles has been a long-debated issue with respect to V2G and battery swapping. Battery degradation is affected mainly by the discharge current, the depth of discharge and the temperature of operation (Taibi and Fernández, 2017). But recent tests have shown that battery degradation with V2G is limited if the battery stays within a state of charge of around 60-80%. The impact is similar to normal AC charging.

The Warwick University degradation battery model that predicts capacity and power fade over time showed that with a V2G system, EV battery life can be extended by using profiles that are V2G friendly.

"Smart grid" algorithms developed within this project allow drivers to monitor how much energy can be taken from the vehicle's battery without negatively affecting it, or even to improve its longevity (Smart Cities Connect, 2017).

The fact that original equipment manufacturers (OEMs) with vehicle-to-everything (V2X) functionality maintain their battery warranty for vehicles with fast charging and/or V2X is a testimonial of confidence gained from several years of market experience. This has been confirmed by one-year intensive testing at ENGIE Laborelec that showed that there was no visible impact of V2X on battery ageing (De Vroey, 2016).

However, battery suppliers today usually mention the global market for their technology – as mobility or stationary – and some indicate a specific application. The suitability of a technology for any given application is difficult to ascertain without testing.

As an example, even if lithium-metal-polymer (LMP) chemistry is said to be used only for mobility today, some suppliers open the market to stationary applications, even if it seems unreasonable due to the high temperature needed to operate. Therefore, the uses of battery technologies for mobility and for utility-scale applications could also diverge in the future.

Table 5: Comparison of batteries for mobility with other batteries

Application		Renewable storage	Ancillary services		Back up		
Battery acceptance		High DoD	50%SoC +	Low DoD	Low C-rate +	Long standby at high SoC +	70%DoD
Li-ion*	NCA	✓	✓	✓	✓	✗	✓
	NMC	✓	✓	✓	✓	✗	✓
	LFP	✓	✓	✓	✓	✗	✓
	LTO	✓	✓	✓	✓	✗	✓
Lead Acid		✗	✓	✓	✓	✓	✓
Redox Flow		✓	✓	✓	✓	✗	✓
LMP*		✗	✗	✗	✓	✗	✓
ZEBRA**		✗	✗	✗	✓	✗	✗

** Different chemistries of lithium batteries: Nickel cobalt aluminium oxide (NCA), nickel manganese cobalt (NMC), lithium fe/ iron phosphate (LFP), lithium titanate oxide (LTO).*

** Lithium metal polymer & zeolite battery research africa (ZEBRA): Such technologies could theoretically be used for ancillary services, but cannot be in practice due to high working temperature.*

Note: DoD (Depth of discharge), SoC (State of charge), C-rate (Cycling rate)

While Li-on is currently the best-suited technology for grid applications, evolutions in alternative battery technologies prompted by vehicle producer demands as well as issues with lithium could substantially impact the ability of EV batteries to provide grid services. A number of technical challenges would need to be overcome to maintain the grid-related capabilities with these technologies.

Types of smart charging and their implementation

Smart charging includes different pricing and technical charging options. The basic technical options are summarised in Figure 13, and the full-fledged options are summarised in Table 6, together with their possible uses and level of maturity.

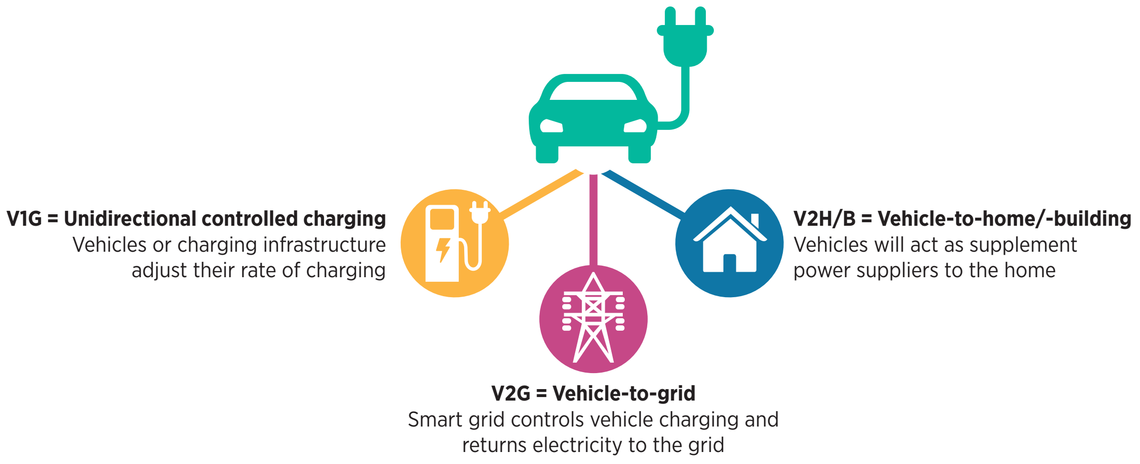
The simplest form of incentive – *time-of-use pricing* – encourages consumers to defer their charging from peak to off-peak periods. It has relatively low technical requirements for implementation (smart meter integrated in the EV or EVSE), and it proves to be relatively effective at delaying EV charging until off-peak hours at low EV penetration levels (ICCT, 2017a). However, simple time-varying electricity price structures might create pronounced rebound peaks in the aggregate residential demand (Muratori and Rizzoni, 2016).

Direct control mechanisms enabled by the EV and the charging point will be necessary as a long-term solution at higher penetration levels and for delivery of close-to-real-time balancing and ancillary services. Such mechanisms range from basic switching on and off of the charging or *unidirectional control of vehicles or EVSE (also called V1G)* that allows for an increase or decrease in the rate of charging, to more challenging bidirectional *vehicle-to-everything (V2X)*.

For V2X, two specific configurations are particularly relevant:[5]

- Vehicle-to-home (V2H) or vehicle-to-building (V2B) do not typically directly affect grid performance. The EV is used as a residential back-up power supply during periods of power outage or for increasing self-consumption of energy produced on-site (demand charge avoidance).
- Vehicle-to-grid (V2G) refers to providing services to the grid in the discharge mode. The utility / transmission system operator may be willing to purchase energy from customers during periods of peak demand, and/or to use the EV battery capacity for providing ancillary services, such as balancing and frequency control, including primary frequency regulation and secondary reserve.

Figure 13: Forms of smart charging



---

[5] There may be also V2Tool / V2Load, where the EV battery directly powers an adjacent load (without any power network/system involved).

The difference between unidirectional V1G and bidirectional V2G is illustrated in Figure 14. In the V1G, the driver, the EV charging site host or the aggregator can be rewarded only for adjusting their rate of charging up and down compared to the initial charging power (3 kW is assumed for illustration). In V2G, EVs can charge and discharge electricity from and to the grid, respectively. The size of the "bids" for grid services corresponds to the capabilities of the EV and the requirements in the given market.

These approaches may be combined – for example, time-of-use tariffs can be deployed with V1G automation to achieve a more effective response. Some of the new charging stations are equipped with both V1G and V2G capabilities (Virta, 2017).

Unlike more mature V1G solutions, V2X has not yet reached market deployment, with the exception of Japan where commercial V2H solutions have been available since 2012 as back-up solutions in case of electricity black-out (in the aftermath of the Fukushima tragedy).

In the US, pre-commercial solutions exist as a support to the grid in locations with weak electrical infrastructure. In Europe, several pilot projects are being undertaken, motivated mainly by local energy management, for example in Denmark, Germany, the Netherlands (Amsterdam) and Spain (Malaga). As of early 2019 several auto manufacturers (*e.g.*, Nissan, Mitsubishi, Toyota, BYD, Renault) were actively involved in V2X initiatives, as detailed in the following sub-section.

Figure 14: Example of unidirectional (V1G) versus bidirectional (V2G) grid services provision

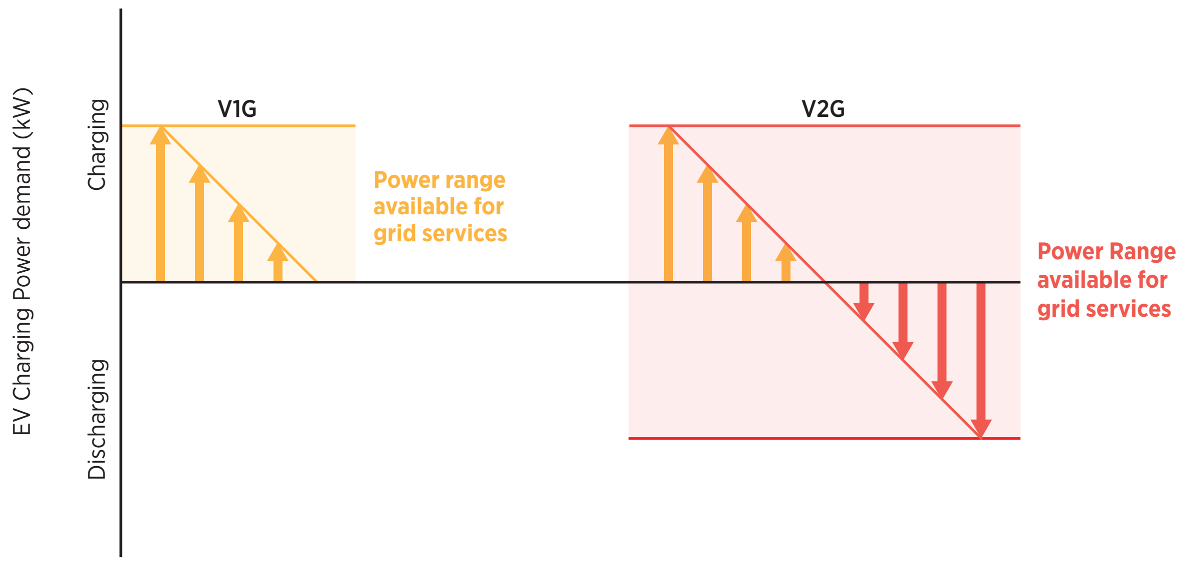


Table 6: Types of smart charging

Type of application	Smart control over charging power	Possible uses	Maturity
Uncontrolled but with time-of-use tariffs	None	Peak shaving with implicit demand response; long-term grid capacity management (both transmission and distribution system operators)	High (based on changes in charging behaviour only)
Basic control	On/off	Grid congestion management	High (partial market deployment)
Unidirectional controlled (V1G)	Increase and decrease in real time the rate of charging	Ancillary services, frequency control	High (partial market deployment)
Bidirectional vehicle-to-grid (V2G) and grid-to-vehicle (G2V)	Instant reaction to grid conditions; requires hardware adjustments to most vehicles and EVSE	Ancillary services including frequency control and voltage control, load following and short-duration integration of renewable energy	Medium (advanced testing)
Bidirectional vehicle-to-X (e.g., V2H/V2B)	Integration between V2G and home/building management systems	Micro-grid optimisation	Medium (advanced testing)
Dynamic pricing with EVs (controlled)	EVSE-embedded meters and close-to-real-time communication between vehicle, EVSE and the grid	Load following and short-duration integration of renewable energy	Low

Smartly (dis-)charged EVs can help to reduce VRE curtailment and emissions, to improve local consumption of VRE production and to avoid investment in peaking generation capacity and mitigate grid reinforcement needs.

Current smart charging projects

The following analysis is based on results of relevant smart charging pilot projects deployed worldwide (Table 7). Most of them are based on slow charging.

Time-of-use tariffs

The most experience exists with dedicated time-of-use charging for EVs. It demonstrates that the wider the price differential between the peak and the off-peak is, the more effective the rate design is. The setting of the peak and off-peak (or even "super off-peak") corresponds to the characteristics of the local electricity system.

Figure 15 presents an example of rates from Pacific Gas & Electric (PG&E) in California (a region with limited solar PV shares) where the peak occurs in early afternoon due to high air conditioning, which may change in the future when solar PV penetration increases.

In most cases, drivers can pre-set the charging for off-peak hours through an app or the on-board system of the vehicle. Customers either have a single meter for home and EV charging or a dual meter. Dual metering – *i.e.*, metering that makes it possible to distinguish the EV consumption from the rest of consumption (by having one meter for the EV plug and one for the rest of the consumption) – has proven to be more successful in terms of the impact on customers' charging behaviour (RMI, 2016).

Table 7: Overview of smart charging deployment and pilot projects

Type of charging	Examples of projects
Uncontrolled time-of-use tariffs	China, Germany, Japan, the UK, the US
Basic control	My Electric Avenue, Scottish and Southern Energy Power Distribution and led by EA Technology, UK (100 households testing Esprit system)
	· Pepco, Maryland, US: 200 households · Consolidated Edison, New York, US: off-bill incentive for managed charging · Xcel Energy, Minnesota, US: 100 households
	United Energy – Victoria, Australia (2013)
Unidirectional controlled (V1G)	Green eMotion, the EU project (2015): reduction of grid reinforcement cost by 50%
	Sacramento Municipal Utility, California, US: reduction of grid upgrade expense of over 70%
Bidirectional vehicle-to-grid (V2G)	eVgo and University of Delaware project in US with transmission system operator PJM, led by Nuvve; Interconnection – commercial operation
	Nuvve, Nissan, Enel, in England and Wales with transmission system operator National Grid – operating pre-commercially
	Nuvve, DTU, Nissan, PSA, Enel project in Denmark, with transmission system operator energinet.dk ("Parker Project") – operating trial
	Nuvve, NewMotion, Mitsubishi project in the Netherlands, with transmission system operator TenneT – commercial trial
	Jeju, Republic of Korea project developing fast and slow V2G; Toyota city project with 3 100 EVs
	Renault, ElaadNL and Lombo Xnet, project in Utrecht, the Netherlands – AC V2G
Bidirectional vehicle-to-X (*e.g.*, V2H)	ElaadNL and Renault in Utrecht, the Netherlands: 1 000 public solar-powered smart charging stations with battery storage around the region in the largest smart charging demonstration to date. Increase in self-consumption from 49% to 62-87% and decrease in peak of 27-67%
	DENSO and Toyota intelligent V2H (HEMS and V2G integrated model), Nissan (V2H) – all of Japan (7 000 households, commercial operation)
Dynamic pricing with EVs (controlled)	Nord-Trøndelag Elektrisitetsverk Nett in Norway
	San Diego Gas & Electric in California: trialling prices posted one day ahead
Second-life battery	BMWi and PG&E ChargeForward pilot programme in California

Based on project and company websites.

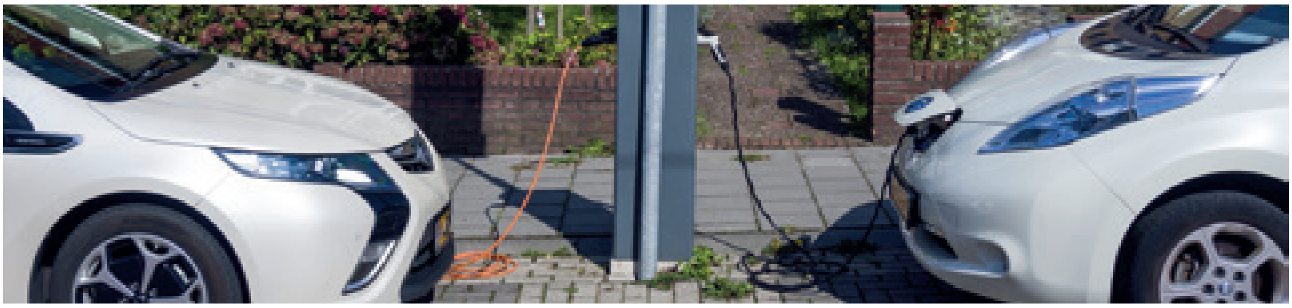
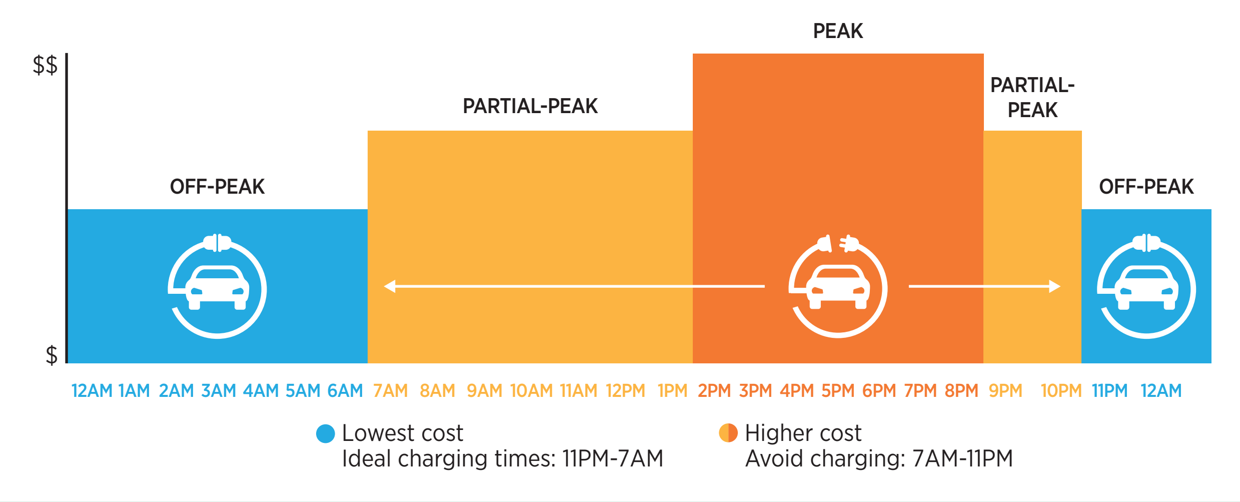


Figure 15: Example of time-of-use charging



Source: PG&E, 2018.

Alternative methods are available on the market that can facilitate the implementation of EV-specific rates without adding the cost of secondary utility meters. The Minnesota Public Utilities Commission permitted Xcel Energy to undertake a pilot that aims to reduce the upfront cost burden for customers looking to opt into EV tariffs by implementing the tariff directly with an "embedded metering" in EVSE (Nhede, 2018).

V1G and dynamic pricing

As the penetration of both VRE and EVs increases further, appropriate market signals will be needed to incentivise loads – including EVs – to adjust their consumption patterns. V1G may be combined with dynamic pricing (prices reflecting the real-time cost of energy and the grid at hourly or even smaller time intervals) supported by automated solutions on the consumer side.

While, for instance, in the Netherlands most of the charging stations already have V1G capability, in other countries it is not yet commonplace. San Diego introduced a pilot programme combining VGI and dynamic pricing, as described in Box 5.

V2X charging experience

Like dynamic pricing, the experience with V2X is limited mostly to pre-commercial deployments. Box 6 provides an example of V2G advancements.

One exception is Japan, where Nissan brought to market a kit that is compatible with the LEAF and is able to provide back-up power for a Japanese home using the CHAdeMO technology, the only international standard enabling V2X. As CHAdeMO has standardised the V2X protocol, multiple systems manufacturers and OEMs followed suit, and some 7 000 units of such V2H systems based on the CHAdeMO protocol have been sold to date. Considering daily average Japanese home consumption of 12 kWh (Briones *et al.*, 2012), the LEAF's 40 kWh battery capacity could provide more than three days of power.

V2G is in most applications deemed to have higher potential commercial value than V2B or V2H (Kempton, 2016). In addition to providing ancillary services and back-up power (Figure 16), it can be used for peak shaving. If EVs could be charged during off-peak times and then discharged selectively to "shave the peak", the utility could potentially forego the need to start up a peaking plant and build additional peak capacity (Figure 17) (Weiller and Sioshansi, 2016).

V2G is particularly relevant for slow charging in areas with a high concentration of EVs, such as large parking lots.

To provide flexibility services, flexibility from single EVs typically needs to be aggregated. For EV services provision to be viable at the wholesale level (peak shaving and ancillary services), capacities of at least

Box 5: SAN DIEGO GAS & ELECTRIC VEHICLE-GRID INTEGRATION PILOT

San Diego Gas & Electric (SDG&E) launched a VGI pilot project that tests making fleets of EVs available as dispatchable distributed energy resources to improve the stability of the grid. SDG&E will install and operate 3 500 charging stations throughout the San Diego region, mainly Level 2 (slow) charging stations, with a large share at multi-unit dwellings.

The programme explores dynamic pricing and, through an app, incentivises charging activities at moments of high renewable energy (Turpen, 2016). Dynamic hourly rates are posted on a day-ahead basis, and they reflect both the system and local grid conditions. An app matches customer preference with those prices. For simple time-of-use, bigger effects were recorded for customers with separate EV-only meters (RMI, 2016).

Box 6: NUVVE, THE VEHICLE-TO-GRID PIONEER

One of the most advanced players in the V2G area is Nuvve, which is now commercialising the technology that was first described in 1996 and further developed by Professor W. Kempton of the University of Delaware. Nuvve claims to have the only EV battery technology that enables any EV battery to generate, store and resell unused energy back to the local electric grid.

Since the first experiments in 2005, the company now has a future-proof solution ready for scaling up and forecasting at different intervals (seconds, minutes, day-ahead corresponding to the market). Nuvve already supplies a wide range of services to the power system (transmission system operators, etc.) including frequency and supply reserve capacity in different markets. It has been participating in the PJM (Pennsylvania-Jersey-Maryland) frequency market since 2009.

Customers do not need to commit to specific times of driving; they just provide information on when they need the vehicle. Nuvve does not control the vehicle, so there is no obligation that would limit customers from driving in case of emergency, etc. Nuvve works with regulators all around the world to address regulatory gaps for V2G using real data from simulations.

Figure 16: Effect of EV battery used as a back-up for the grid

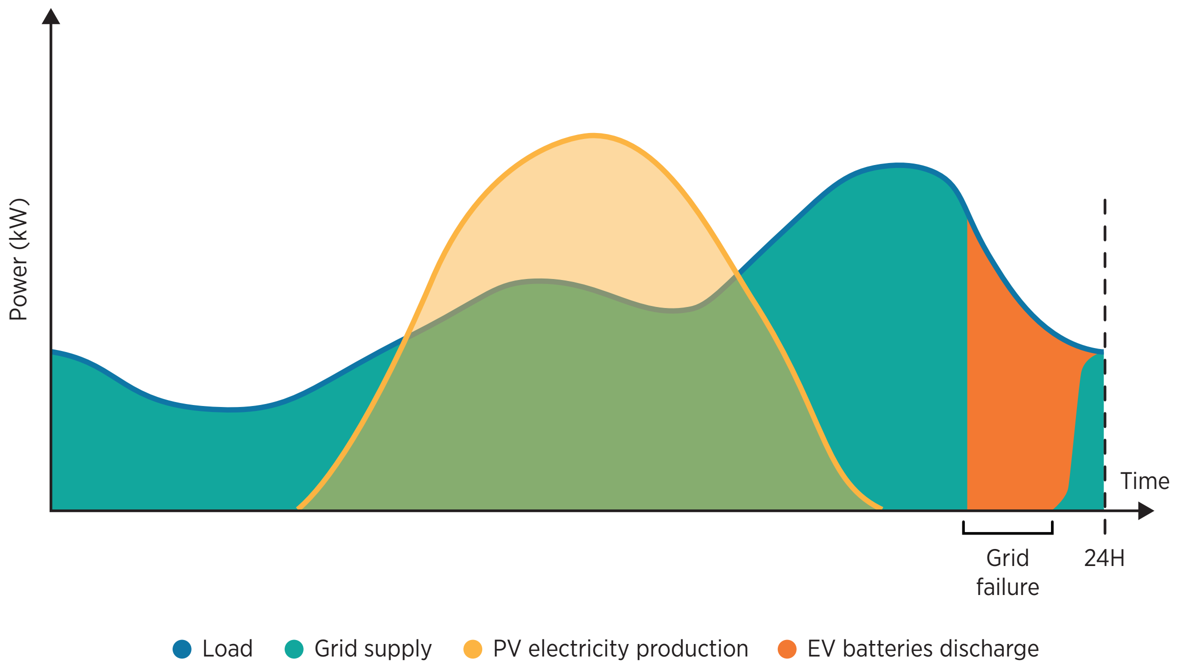
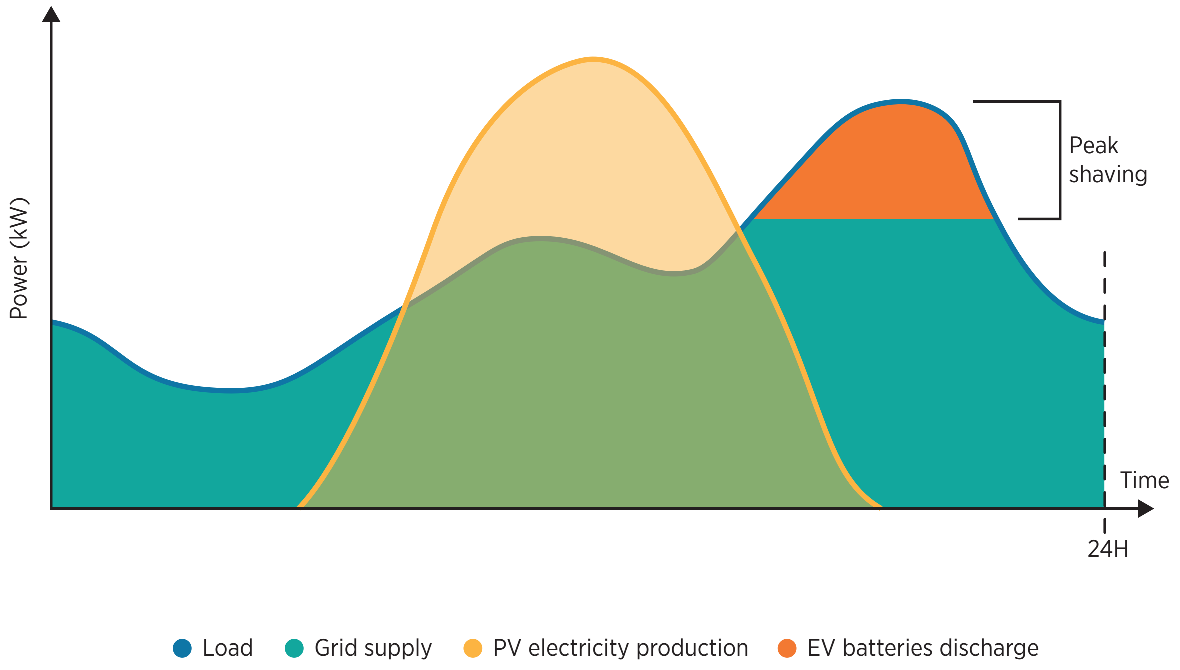


Figure 17: Effect of peak shaving



1 MW to 2 MW would have to be traded in each V2G transaction – that is, roughly the equivalent of 500 EVs connected to a standard 3.7 kW European circuit. Considering that these EVs are not always available, the number of controlled EVs would need to be even much higher (Weiller, and Sioshansi, 2016). More examples of V2G projects are given in Box 7.

Benefits of smart charging can be further amplified in isolated systems, as detailed in Box 8.

VGI with fast charging

Fast charging (*i.e.*, charging at high power) applications generally have very low potential for VGI even though it is technically possible. When fast charging is needed, there is no real flexibility option (short charging time), and peak load at highway stations does not and will not coincide with conventional peak load. The impact of fast charging on the grid will need to be mitigated by installing charging points in areas with low impact on local peak demand and congestion while achieving a high utilisation rate (for profitability).

However, in some specific applications, fast charging could occur at other moments. For example, an electric bus driver having the opportunity to charge at several bus stops might choose not to charge if this flexibility has a value and is not impacting the driver. The flexibility related to fast charging of electric heavy-duty vehicles will be investigated under the four-year EU project ASSURED, started in 2017. The project will test innovative heavy-duty and medium-duty vehicle solutions with different interoperable charging infrastructure concepts that will be developed into business cases, considering commercial as well as societal costs and benefits.

Local optimisation also can be achieved by combining fast charging with stationary batteries and locally installed VRE. When fast charging is required, the EV user is not expected to authorise much flexibility in time or power; however, combining fast-charging

Box 7: EXAMPLES OF VEHICLE-TO-GRID PROJECTS

- In February 2019 the City of Hamburg launched the "ELBE" project, which focuses on funding the installation of EV charging stations at buildings and on commercial premises. The project includes the application of V2G technology and load-dependent tariffs where EVs are considered as controllable consumption[*].

- Nissan and Enel partnered to implement an energy management solution that uses V2G charging units and allows vehicle owners and energy users to operate as individual energy hubs, able to draw, store and return electricity to the grid. Two pilot projects were launched in Denmark (Parker Project) and in the UK to test the solution. Throughout 2016 owners of Nissan EVs earned money by sending power to the grid through Enel's bidirectional chargers, and the Danish and UK transmission system operators benefited from primary regulation grid services (Enel, 2016). The yearly frequency response revenue per vehicle was around EUR 1 400.

- At the end of 2017 Mitsubishi announced a V2G pilot project utilising the battery packs of more than 25 000 PHEV Outlanders in the Netherlands. The project will be implemented in co-operation with the grid operator TenneT, the EV smart charging solution provider NewMotion and the V2G tech and grid-balancing services provider Nuvve. As in the example of Nissan in Denmark, the role of Mitsubishi will be to provide capacity reserves through the connection of PHEV Outlanders to the grid (Ayre, 2017).

- Unlike the other pilots that focused on direct current (DC) V2G, a pilot in Utrecht in the Netherlands by Renault, Elaad and Lombo Xnet tested AC V2G. A standard that is still in the drafting stage, ISO 15118 Ed2, would enable charging stations other than CHAdeMO to implement V2G functionalities. However, this would require charging stations that can communicate, as well as vehicles with bidirectional power flow capabilities, and both the charging stations and the vehicles would have to implement ISO 15118 Ed2. The trial included the world's first solar-controlled, bidirectional AC charging station. Provision of reserve power resulted in monetary benefits in the range of EUR 120 to EUR 750 annually per EV owner (de Brey, 2017).

---

[*] https://elektromobilitaethamburg.de/

Box 8: SMART CHARGING IN ISLAND SYSTEMS

Island power systems have been pioneers in studying advanced distributed energy resource applications, including VGI, for several reasons. Islands are often highly dependent on fossil fuels, with petroleum-derived fuels representing a major share of the total primary energy use (the inclusion of more traditional sources is limited).

While each isolated system is different in terms of weather, population and economic activity, the response to power system shocks in island regions is generally "tighter" – that is, the loss of a few electricity supply units has a bigger impact than in interconnected systems, and the effects of voltage drops are more significant. As a result, balancing the grid is more difficult, the risk of load shedding and black-outs is higher, and more reserves are required (Ramírez Díaz *et al.*, 2015). Introducing high shares of VRE on their own thus represents a challenge for system stability.

At the same time, many tourist islands already operate fleets of rental cars that represent a suitable use case for electrification (a limited number of chargers needed across the island) and are being used as distributed energy storage systems.

The synergies have been demonstrated by a number of studies:

- In the island of Barbados, an EV scenario for 2030 with solar and wind supply covering 64% of demand and more than 26 000 EVs in the system demonstrated a five times lower production cost with the most efficient smart charging strategy compared to uncontrolled charging. Even uncontrolled charging would lead to higher level of curtailment, even if lower than the reference scenario without EVs – that is, EVs are still partially charged with VRE (Taibi and Fernández, 2017).
- Modelling of Tenerife (Canary Islands, Spain) showed that the impact of 50 000 EVs would increase the renewable share in the island's electricity mix up to 30%, reduce CO_2 emissions by 27%, reduce the total cost of electric generation by 6% and reduce the oil internal market by 16% (Ramírez Díaz *et al.*, 2015).
- Modelling of São Miguel in the Azores archipelago (Portugal) showed that EVs could help increase renewable energy production (Camus and Farias, 2012).
- Samsø Island (Denmark) would allow even up to 100% renewable energy generation by using EVs as well-to-wheel zero-emission vehicles (Pascale-Louise Blyth, 2011).

infrastructure with stationary energy storage can increase the flexibility of the station vis-à-vis the grid, through buffering. A solar canopy and stationary storage can be integrated in a charging infrastructure or even in the charging points themselves, as a support for the use of (typically high-power) charging points. This helps limit power consumption from the grid, avoid high demand charges (*i.e.*, increase self-consumption) and allow higher charging peaks with limited grid impact.

For example, in the US, joint projects between the charging station provider ChargePoint and the energy storage company Green Charge Networks are using on-site batteries and EV-charger scheduling to control and smooth out the grid demand of charging stations, helping their hosts avoid incurring costly demand charges (St. John, 2015).

Tesla is partnering with utilities on grid energy storage, with Supercharger stations acting as a "grid buffer". A 0.5 megawatt-hour (MWh) battery pack next to the Supercharger station means that the cars can be charged directly from that pack without the electricity grid seeing the spike (Herron, 2013). Fastned in the Netherlands equips its fast chargers with a solar canopy and storage to offset the electricity demand.

3.3 Charging infrastructure

Current charging infrastructure

The type of charging is one of the relevant factors determining the availability of EV flexibility.

Whereas AC power flows through the electric distribution grid, EV batteries require DC power. An AC/DC converter (or charger) is therefore always necessary. This converter can be located in the charging point ("off-board charger") or in the vehicle ("on-board charger"). The choice between off-board or on-board charger is a trade-off between the cost of the charging station (on-board is cheaper) and the vehicle (off-board chargers reduce the weight and cost for the converter in the vehicle). AC current is also more easily available (the type of current coming from the socket), so, all else equal, an on-board charger means that more locations are available for charging.

The most common power output levels of EVSE, and charging modes based on the use of different communication protocols between the vehicle and the charger, are summarised in Annex 2.

- For low power (typically up to 22 kW) – *i.e.*, Level 1 and Level 2 in North America and "slow" or "normal" chargers in Europe – on-board chargers are deployed in most cases. They enable the EV to charge on conventional connectors or on low-cost AC charging points.

- The intermediary power range (from 22 kW to 50 kW) was initially not used much, and when deployed, the AC solution was chosen (*e.g.*, Renault up to 43 kW AC). However, an increasing number of charging solution providers propose DC charging (off-board charging) in this intermediary power range. This new trend might have a strong impact on the deployment of AC charging solutions. However, there is no consensus right now from the perspective of vehicle OEMs.

- For high power ("fast chargers", typically starting from 50 kW), off-board chargers are deployed in most cases. The AC/DC converter, being bigger, heavier and more expensive with increasing power, is then located in the charging point and mutualised between the vehicles). Heavy-duty vehicles, especially urban buses, when they charge at intermediate stops or end stops, typically use pantographs at 150-300 kW.

Fast and ultra-fast charging would be a priority for the mobility sector. However, slow charging is better suited for smart charging than are fast and ultra-fast charging. Furthermore, fast and ultra-fast charging may increase the peak demand stress on local grids. Solutions such as battery swapping, charging stations with buffer storage, and night EV fleet charging might become relevant in combination with fast and ultra-fast charging.

Table 8 provides a summary of current ultra-fast charging projects. Many electric cars are already able to charge at 50 kW. For instance, Tesla has its own charging infrastructure up to 140 kW. ChargePoint's Express Plus is a modular, scalable DC fast-charging platform that can deliver 62.5 kW to 500 kW as charging needs increase. Electric buses are charging with power capacities typically ranging from 22 kW up to 300 kW. DC charging is used for high-power charging of electric cars and for electric buses.

The main charging locations are at home, work and semi-public or public places. Most of the time, AC charging is implemented. At home, low power is usually sufficient (*e.g.*, 3.7 kW on a 240 V circuit) and AC chargers are deployed. If higher power is required, or if an objective of maximum self-consumption is followed (*e.g.*, with local solar PV production), intermediate power AC or DC charging stations are installed (7.4 kW to 11 kW). DC high-power charging is often deployed along highways, but some cities are also deploying it for street charging (*e.g.*, Belib in Paris).

Smart charging infrastructure outlook

As battery ranges increase, cable charging will likely remain the most common charging technology for light-duty vehicles for years to come. As EVs progressively reach the driving range of ICE vehicles, charging time will become a more critical issue, putting further pressure on both battery cycling and EVSE infrastructure innovations. At the same time, high ranges will be used only to a limited extent, implying only limited needs for ultra-fast-charging, even with mobility-as-a-service (MaaS) and the expansion of autonomous vehicles, due to high cost. Slow (up to intermediate power range) home and hub charging will prevail.

Table 8: Overview of major ultra-fast charging infrastructure projects by OEMs and utilities

Location	Coalition	Type of companies	Plans	Maturity
Global	Tesla	Integrated mobility company	> 1 000 stations today; plans to extend to 10 000	145 kW today (120 kW by car)
China	State Grid of China	State-owned utility	160 000 public charging points today; plans to build 10 000 charging stations / 120 000 charging poles by 2020	Up to 360 kW
Europe	Ionity: BMW, Ford, Mercedes, Volkswagen, Audi, Porsche	OEM joint venture	400 by 2020	Up to 350 kW
Europe	Allego and Fortum	Charging infrastructure provider and utility	322 ultra-fast chargers and 27 smart charging hubs by 2020	Up to 350 kW
Europe	E.ON and Clever (Denmark)	Utility and e-mobility service provider	180 by 2020	150 kW
Europe	Enel	Utility (Italy)	900 today; 7 000 by 2020; 14 000 by 2022	22 kW (quick); 50 kW (fast); 150 kW (ultra fast)
Europe	Open fast-charging alliance	Global consortium of public and private EV infrastructure leaders	> 500	Up to 150 kW
US	Nissan, BMW and Ford funding EVgo	OEMs	> 220	
US	Electrify America, subsidiary of Volkswagen	Non-proprietary solution by OEM	> 300	150-350 kW

Based on project and company websites.

Alternatives to conductive charging will develop between 2030 and 2050, both for light-duty vehicles triggered by MaaS and autonomous driving, and for trucks as well as buses. Continuous static charging is likely to bring major innovation but without major impact on grid flexibility.

Charging infrastructure outlook: Towards higher charging power

By around 2024, driving ranges of electric cars of 600 km can be envisaged to turn from a niche to commonplace. Electricity consumption for an EV is about 20 kWh per 100 km (less for a small car at slow speed). A 1 000 km range, as announced for the new Tesla Roadster, would require a battery of about 200 kWh.

Compared to the first generation of electric cars in the early 2010s, battery capacity has increased dramatically. Initially, batteries in the 20 kWh range were introduced. Less than 10 years later this capacity has at least doubled, and the range is up to five times higher. Luxury cars such as the Porsche Mission E announced for 2019, the Audi eTron on sale in 2018 and the Jaguar I-PACE (available in 2018-2019) have or will have batteries of 80-100 kWh. Even larger batteries, for example 120 kWh with the BMW iNext platform, will be possible around 2021.

By 2030 to 2050, EVs should theoretically be able to reach similar ranges as today's diesel cars and beyond. However, the practical need for such ranges and the corresponding increase in charging power may remain limited.

EVs were initially used mostly for urban purposes, with typical driving distances of less than 10 000 km per year. Today, electric cars are driving 15 000 km per year, like average cars or even more. However, for example in the European context, the average daily driving distance is only 30-40 km, with 95% of the trips during a year below 110 km, which means that the currently available driving range is already sufficient (Leemput, 2015).

However, the need to rapidly charge along highways will grow as EVs with higher battery capacity are used increasingly for extra-urban trips and as bigger daily distances are driven. Novel issues such as queues at the public charging infrastructure (already occurring in Norway, for example) – causing frustration for users – may also arise.

For fast charging in 15-20 minutes, even the expected 2018-2019 models will require much higher charging power than is commonly used today (> 200 kW). The industry is making substantial efforts to construct even more powerful chargers, as shown in Box 9.

For a 200 kWh battery, a charging power of 600 kW would be needed if the driver wanted to charge that quickly. With today's chemistry, a battery can charge at 3C (*i.e.*, 20 minutes is needed to charge the battery from 0% to 100% if the same power level was kept)[6]. A 3C rate means that the discharge current will discharge the entire battery in 20 minutes.

Even faster charging (under 15 minutes for 80% of battery capacity) could be possible with better battery chemistry. Breakthroughs in batteries may occur, including the improvement of the C-rate in the coming decades, which may even double the C-rate.

However, it remains questionable what "speed" of fast-charging stations will really be needed. Most vehicles will very rarely drive more than 600 or 1 000 km per day. And if human drivers are at the steering wheel, they will take breaks. Even if EVs are used increasingly for autonomous cars with the longer range, there may be no need to go beyond that range. Driving 1 000 km in an urban area would mean driving for 20 hours (optimistic even for MaaS) at an average of 50 km per hour (a very high speed for an urban area). Today's taxis driving 200 km per day are already considered to have high mileage, even if they drive 16 hours per day (Olsen, 2017).

Box 9: EFFORTS OF CONSORTIA

The goal of an industry consortium named CharIN, led mainly by German auto manufacturers, is to adapt the Combo standard to higher power (350 kW) to be able to charge 80% of the battery in about 15 minutes.

CharIN members include auto companies (*e.g.*, Audi, BMW, Daimler, Ford, GM, Honda, Hyundai, Jaguar-Land Rover, Mahindra, Mitsubishi, Opel, Porsche, PSA, Renault, Tesla and VW), utilities (*e.g.*, EnBW), hardware manufacturers (*e.g.*, ABB, Siemens) and charging station operators (*e.g.*, ChargePoint, Shell) (CharIN, 2018a).

The CHAdeMO Association also has been preparing for high-power charging. It published the 200 kW protocol in 2017, and the latest protocol up to 400 kW was published in June 2018. The CHAdeMO Association, established in 2010, has some 400 members from 36 countries, including car companies, utilities, hardware manufacturers, charging station operators and grid-integrated platform service providers (CHAdeMO Association, 2018). In the short term, charging stations of around 150 kW will be deployed.

---

[6] The C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity.

If that is the case, the trade-off between battery size (and related weight and cost) will play an important role despite the expected battery evolutions. For this reason, the battery sizes may remain limited according to their use, especially within fleet management optimisation as MaaS proliferates.

All in all, slow(er) charging at night will remain the most attractive for the grid and for light-duty vehicle drivers despite the possible developments in fast-charging power and battery chemistries summarised in Table 9.

However, advances in battery technology will drive down the cost of typical-use batteries and therefore also the cost of the EVs themselves.

Nevertheless, the concrete patterns will differ for other transport modes such as passenger cars, freight, taxis and buses.

Finally, PHEVs and other sources such as green hydrogen-fuelled vehicles could also be considered as alternatives, not only for passenger cars but also in other applications such as industrial and commercial trucks, buses and taxis.

EV charging will have an impact on distribution grid investments. How much grid investment (in terms of cables and transformers) will be needed in a given location will depend on the characteristics of the local distribution network, including bottlenecks to EV deployment, the methodology of distribution grid sizing by each distribution system operator, the presence of solar PV connected at the low-voltage level, etc. For example, if smart charging is used in such locations, it may be included with lower grid reinforcements than in locations where no electric heating is used. Integration of high shares of solar PV connected at a low voltage level could be facilitated with smart charging, whereas in locations with no or very low shares of solar PV, EVs could increase the strain on local grids.

Impact of transport patterns on charging needs in different cities and regions

Different city transport patterns will also impact charging needs. To a large extent these patterns are determined by the interplay of population density and the level of economic development. In developing, densely populated areas, low-quality road infrastructure and congestion may prevent high uptake of shared mobility. With the upcoming urban growth in Africa and Asia, more and more people will live in cities that are friendly for two-wheelers (and cities may also focus on those, as we already see with motorbike-sharing businesses in Asia). In developed, densely populated areas where infrastructure is in good shape, shared mobility may thrive.

However, in high-income cities with low population density, private ownership may remain the most relevant mode of transport. Table 10 provides a topology of cities and explains how their specifics will affect demand for mobility in the future. It outlines these charging trends in three major city types and corresponding charging needs. Figure 18 provides examples of today's cities for each category (the size of the bubble indicates the size of the city population). These characteristics will also impact the evolution of MaaS and autonomous vehicles.

Bigger car batteries will not by definition require more powerful chargers. Slow charging should be sufficient to charge them overnight. Ultra-fast charging will help overcome customer anxiety and act as a complement. Even autonomous cars under the MaaS scenario that will be parked for less time will most likely not exceed 20 kW charging capacity. Bigger batteries will not always be needed.

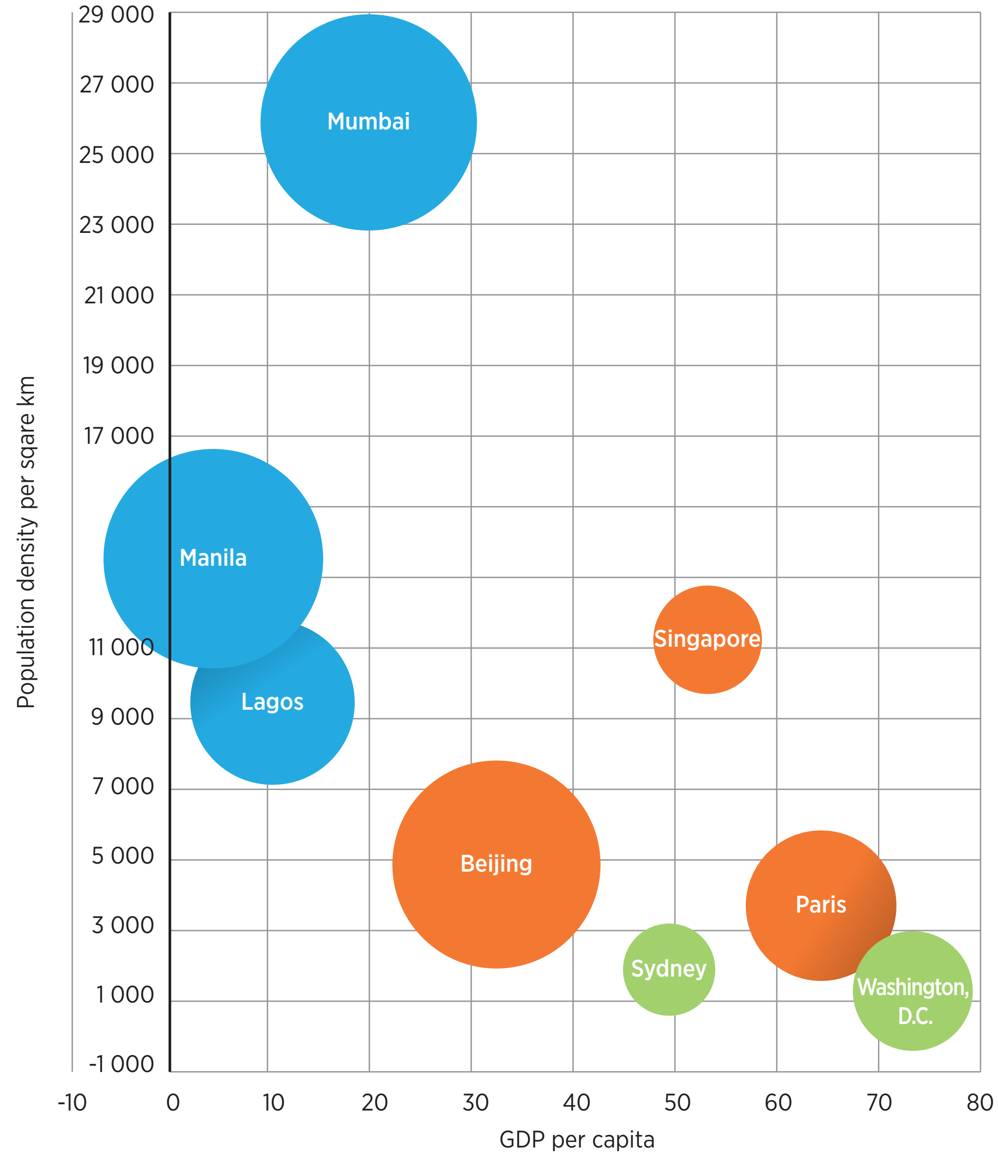
Table 9: Light-duty vehicle ranges and fast-charging power development needs by 2030-2050

	2018	2023	2030-2050
Driving range capabilities (km)	300-400 km	600 km	600 - 1 000 km
Fast-charging development (power/ speed of charging)	150 kW = 750 km/h	240 kW = 1 200 km/h	600 kW = 3 000 km/h

Table 10: 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

Figure 18: Examples of city types



Based on Demographia, 2017.

Charging infrastructure development and related incentives

In theory, public charging infrastructure should become more commercially sustainable as the EV market expands, with business models based on electricity or retail sales combined with grid services and other revenue streams such as advertising. Funding programmes will still be needed in emerging EV markets and to target difficult market segments such as curbside charging stations, multi-unit dwellings and intercity fast charging (ICCT, 2017a).

First, emerging markets with low penetration of EVs may need initial incentives for charging to kickstart the market. For example, Costa Rica introduced incentives in the form of a substantial reduction in import taxes on EVs, but only less than 1 000 EVs were sold because of missing infrastructure (SLoCaT, 2017).

Second, the commercial viability of public charging and thus the need for charging infrastructure incentives will be affected mainly by demographic and housing factors. Data analysis of charging in leading EV markets around the world demonstrated that denser cities like Amsterdam have approximately 1 public charger per 5 EVs, compared to 1 public charger per 25-30 EVs in California (ICCT, 2017a). In some parts of Europe and in Asian megacities, where population densities are high and where most people may not live in buildings with garages and off-street parking, public charging coverage will remain important and may need to be developed as a public service for some time into the future. In Europe, 40% of drivers do not have access to off-street charging points.

But even if that is the case, most drivers will want to have access to "their own" on-street charger, at least if individual EV ownership prevails. Alternatives to building new full-fledged charging points – such as by retrofitting the existing infrastructure of street lights – exist in the market, coming at a fraction of the price of regular charging points. The German start-up ubitricity has been partnering with the local council in London to develop such charging points (Kensington and Chelsea, 2017). However, the local procedures (permits, etc.) are often lengthy and represent barriers to these innovations.

The current grid tariff structure can make up a substantial part of the electricity costs of a fast-charging location. The higher voltage levels required for fast charging often apply higher shares of demand charge. Simultaneous charging events at fast-charging stations thus increase the demand charges by pushing up peak demand. Demand charges can make up over 65% or even up to 90% (RMI, 2016) of the costs.

However, DC fast-charging stations are currently characterised by having a low load factor, with sporadic instances of high energy use due to a limited number of vehicles in the market that will use these stations in the near term. This can subject fast-charging site hosts to significant demand-based charges in conjunction with low utilisation, making the provision of fast-charging solutions during the critical phase of early adoption uneconomic. The next generation of DC fast chargers capable of charging vehicles up to 500 kW is necessary to meet the needs of the evolving EV market but will only exacerbate this issue, especially as transit buses and other medium-/heavy-duty vehicles also transition to electric drive.

This issue can be addressed by local optimisation with renewable energy and storage: co-locating stations at high power demand sites or by installing energy storage on-site to manage peak demand and provide additional network services. Energy can be charged at low demand/tariff times (at night or at times of excess production from renewables) (Mauri and Valsecchi, 2012) and discharged at peak demand times. Peak demand charges can stay the same while the use of the connection in terms of kWh increases.

Therefore, regulation in some countries/regions encourages the inclusion of energy storage and local renewable energy (mainly solar PV) for fast-charging sites to reduce the costs and the need for capacity upgrades (*e.g.*, through power purchase agreements for renewable energy for charging providers in some US states). However, the additional high capital costs of storage can limit the effectiveness of this technique to mitigate demand charges.

Many jurisdictions in the US, such as California and New York, have implemented or are considering alternative rate design options, for example:

- Demand charge could be replaced with or paired with higher volumetric pricing to provide greater certainty for charging station operators with low utilisation. This rate could be scaled based on utilisation or load factor as charging behaviour changes over time with increased EV adoption.

- A monthly bill credit representing a percentage of the nameplate demand associated with installed charging infrastructure behind a commercial customer's metered service.

- A retroactive and variable credit based on the difference of the effective blended per kWh distribution charge, including demand charges, and an agreed upon target blended rate, multiplied by the volumetric energy throughput in each billing cycle for commercial customers with dedicated EV charging stations (*e.g.*, Long Island Power Authority in New York).

Lower grid fees because of higher voltage connection level and the possibility to charge electricity wholesale prices at fast-charging stations (versus end-consumer/retail prices charged at home or offices) also may become increasingly relevant with increasing demands for charging power, and could eventually bring down the prices of fast charging.

All in all, regulation will need to strike the right balance to allow utilities reasonable and prudent recovery of costs while at the same time encouraging sites to deploy and operate DC fast chargers. Incentives for multi-level dwelling charging infrastructure will also play an important role. Because wiring of the building represents up to 50% of the charging installation cost, integrating pre-cabling for EV charging equipment of a certain level in any new construction can substantially relieve such barriers.

Countries and cities can mandate that a certain percentage of new or retrofitted parking spaces be "EV ready" through requirements in building codes. With zoning regulations, cities can influence where and how many EV charging stations can be installed in each area. This is a key lever that can influence the availability of charging infrastructure in the future when the lack of multi-level dwelling and workplace charging could become a significant barrier to adoption and could restrict electrification of transport.

Such measures have been already implemented in some regions of the US. For example, the California Green Building Standards Code of 2015 requires 6% of all parking spaces in commercial buildings to include infrastructure for EVs and has since been extended further. In Los Angeles, 240 V outlet and circuit capacity for Level 2 chargers is mandatory for every new building (ICCT, 2017a). Atlanta's new ordinance requires 20% of charging spots in commercial buildings to be EV ready as well as electrical infrastructures in new residential buildings to support EVs (Pyzyk, 2017). Ontario, Canada requires 20% of parking in all new non-residential buildings to have full circuit capacity to support EV charging (Ontario, 2018).

Several initiatives to increase the number of charging stations in major cities across Europe have been launched (*e.g.*, Amsterdam, London, Paris). The EU made ambitious proposals in this respect. Even though these were eventually substantially watered down, the new EU-wide buildings legislation requires at least one charge point (instead of the originally proposed 10% of parking spaces) in non-residential buildings to be equipped with charging points ready for smart charging. In addition, new and renovated residential buildings with more than 10 parking spaces must include the pre-cabling to enable the effortless future installation of EV charging points for every parking space.

Even though direct incentives for EV purchases may be progressively phased out in most locations within the 2030 time horizon, incentives for charging infrastructure are likely to remain to kickstart markets or to address complex market segments such as ultra-fast charging and multi-unit dwellings. In addition, local authorities will have to streamline permitting procedures for charging.

Alternatives to cable charging

In addition to the evolution of cable charging power, a number of charging technology innovations with high potential are already emerging and will be available in the future.

Static wireless charging is being developed. There is some limited deployment of this technology for buses and projects for cars. However, it suffers from lack of standardisation and from its higher cost and slightly lower efficiency. Some possible issues with electromagnetic compatibility and safety also have to be addressed. Currently, the maximum power of wireless charging is lower than with conventional charging (by cable or pantographs): 200 kW for buses (*e.g.*, Bombardier PRIMOVE) and 11 kW for cars (*e.g.*, WiTricity).

For long-distance trucks and buses, the current battery technology does not enable long-distance trips without frequent charging (possibly every 100-200 km for trucks and every 100-300 km for buses with technology available in 2017) at high power (> 500 kW), which makes their electrification less attractive. Autonomous vehicles also will require new charging solutions.

For these reasons, continuous charging and battery swapping are being explored. Their emergence is difficult to assess because of uncertainty regarding the improvement of battery technology (increase in density) and their cost reduction in the long term.

Continuous charging

Both conductive and inductive continuous charging are potentially attractive:

- *Conductive charging* uses conductive power transfer. It requires the use of a charging board as the power transmitter to deliver the power, and of a charging device, with a built-in receiver, to receive the power.

- *Inductive charging*, also called wireless, uses an electromagnetic field to transfer energy between two objects through electromagnetic induction (Figure 19).

Conductive charging requires metal-to-metal connection. It can be done through the static ground-based system with conductive plates, for which Alstom is developing a product based on its experience with trams (ELinGo, 2018). Another alternative is using *catenaries* on some tracks, as Siemens is testing with the "eHighway". These technologies can potentially reduce the battery size, enabling cheaper and lighter heavy-duty vehicles with more passenger capacity (buses) or freight capacity (trucks). However, they still are at a lower maturity level compared to traditional pantographs conveying current from overhead wires. Moreover, they require more investment to adapt the roads (estimated at EUR 1-2 million/km for catenaries).

Continuous charging also can be done wirelessly, as tested for example in the Republic of Korea and in Belgium in a pilot project with buses and with the Renault Kangoo.

Static wireless (inductive) charging may become more common in mass applications, including already in the short term (around 2020) for luxury cars. For example, a solution by WiTricity should be part of BMW's 530e announced for 2018 (Sullivan, 2018).

Drawing power continuously from the grid in real time from electrified roadways through dynamic wireless charging could potentially increase the availability of flexibility (Suh and Cho, 2017). Impacts of continuous wireless charging on flexibility need to be investigated further.

Autonomous vehicles are more convenient with automated charging, with static wireless charging being the most mature technology among those. If that is the case, the autonomous vehicle drive range and the available time for charging will be the key parameters to consider regarding grid impact.

Pros and cons of wireless charging are presented in Table 11.

The ongoing standardisation efforts in this area include:

- International standard IEC 61851-23-1: Electric vehicle conductive charging system – Part 23-1: DC Charging with an automatic connection system: this norm will cover the implementation of pantograph charging for electric buses.

- International standard IEC 61980 series – a work in progress, covering the wireless charging topics.

- Charging standards for electric buses – as discussed in, for example, the EU project ASSURED.

The 2030 and 2050 outlooks for different types of EVs are summarised in Table 12. Different charging solutions according to the type of vehicle and power needs are further detailed in Annex 2.

Table 11: Pros and cons of wireless (inductive) charging

Advantages	Drawbacks
· Smaller battery sizes with opportunity charging (*e.g.*, at traffic lights) · No need for charging cables · Fewer charging points crowding up streets · Good combination with autonomous vehicles	· Limited efficiency (max. 90% today) · Need for infrastructure build-out · Need for proper alignment between transmitter and receiver · Cars still need conductive charging "just in case": more complexity, more parts

Figure 19: Inductive charging

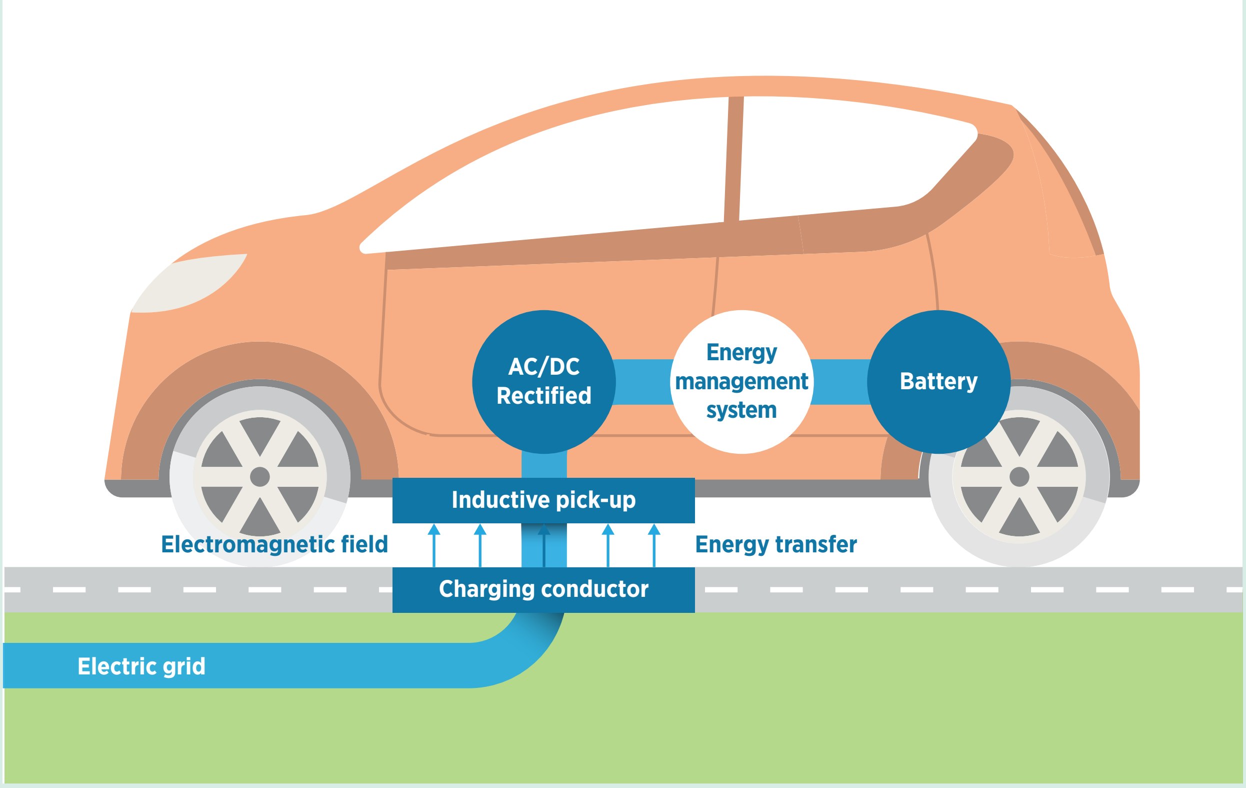


Table 12: Overview of the charging solutions for cars and heavy-duty vehicles

Type of vehicle	2020	2030	2050
Electric car	· Cable charging (3-150 kW) · Static wireless charging for some luxury cars (3-11 kW) · Dynamic wireless charging, ground continuous charging at pilot level	· Cable charging (3-350 kW, possibly higher power) · Static wireless fast charging · Continuous charging for cars probably not widespread because of battery improvement	
Electric truck	· Cable charging (40-150 kW) · Static wireless charging (up to 200 kW) at pilot level · Continuous charging with catenary at pilot level	· Winning technology depends on battery improvement · For urban trucks: static charging (cable or wireless) at night or stops · For long-haul trucks: continuous charging is an option if battery does not improve quickly, due to lower cost	
Urban electric bus	· Depot charging with cable up to 50 kW or pantograph (up to 600 kW) · Pantographs at end stations or some intermediary stations (150-600 kW) · Limited commercial deployment of static wireless charging at stops (up to 200 kW) · Continuous charging with pantograph in limited number of cities already having infrastructure (trolleybus or catenaries) · Continuous wireless charging at pilot level	· Depot charging with cable or pantograph or wireless (up to 50 kW) · At stops, charging with pantograph or wireless (up to 1 MW) · Use of continuous charging remains uncertain. If batteries keep improving and infrastructure remains expensive, then deployment would be limited.	

Battery swapping

Battery swapping includes exchanging an EV discharged battery for a charged one, eliminating the need to wait at the station for the EV to charge. The business model is based on leasing / renting / subscription for the use of battery-swapping stations or pay-as-you-go systems for EV batteries. Either the purchase of the car can be separated from the purchase of the battery to lower the cost of acquiring the vehicle, or the owner may remain the owner of the battery. This approach could be used by individuals or by fleets (*e.g.*, public transport).

Battery swapping for passenger vehicles was pioneered by Better Place, an Israeli company with a business model for cars directly inspired by mobile phone schemes (subscription or pay-as-you-go scheme (per kilometre)). Customers would not own the battery; the company would just guarantee a minimum capacity for each battery that it provides. The Better Place model was taken up only by Nissan and Renault – with both offering an integrated battery as well as a battery swapping scheme – and faced a rather tepid reaction from customers. However, this model seems to be coming back for two-wheelers and for fleets.

Battery swapping is better suited for captive fleets that return on a regular basis to the same place where the empty batteries can be replaced by full batteries, and that are composed of a small number of different vehicle and battery models. Pros and cons of battery swapping are presented in Table 13.

Because of technology development, in the future charging providers could operate battery swapping stations or wireless charging roads:

- Battery swapping may proliferate together with fleet development and automation. Reducing a car (taxi, e-rickshaw) or bus' downtime with a swapping station and reducing the total cost of ownership (if the battery is separate from the car/fleet ownership) may help with accessibility and productivity in a

Table 13: Pros and cons of battery swapping

Advantages	Drawbacks
· Very fast refuelling time, whatever the battery size (typically 5-10 minutes) · Batteries stored in the swap hubs can be used to balance the grid	· No standardised batteries: heavy logistics for cars · Battery swap network must be deployed at once: high capital expenditure · Cars still need conductive charging "just in case": more complexity, more parts

number of applications. Battery-swapping stations already exist for buses (mostly in China and the Republic of Korea) and two-wheelers, including the successful start-up Gogoro (Box 10).

The common models are leasing, renting or pay-as-you-go. Battery swapping for trucks (small delivery as well as long haul) also may be developed in emerging markets: the Indian truck maker Ashok Leyland announced a partnership with the transport solution start-up SUN Mobility for the development of interchangeable battery stations powered by renewable energy (Ghoshal, 2017). Tesla also announced such plans in the past to serve its Model S, with the driver owning the battery and the swapping station not operating as a storage station. Standardisation of batteries that would allow the station to serve batteries for various vehicle models with automated battery swapping, as well as the reliability of battery packs, remain important barriers to entry for this model. It may only work when offered as a complete solution (vehicles plus swapping stations) for captive fleets (buses, freight, etc.).

- Another possibility is the operation of wireless charging roads, if the dynamic EV charging technology's potential materialises (Goodwin, 2017; Fagan, 2017), or even of smart motorways, if systems such as flexible security rail and smart signals make it possible to adapt the number of lanes in each direction according to traffic needs.

3.4 Smart charging enablers

Consumer behaviour

Comparing the expectations of technology enthusiasts and the mass market may reveal substantial gap between these different groups of customers. While the former are the frontrunners willing to test new solutions and who aspire to personally contribute to a sustainable society (and even pay a premium for it), the latter favour comforTable and affordable solutions. Digitalisation will help to overcome this gap and will eventually help to break silos between power and energy systems by facilitating smart charging.

Despite the low sale numbers to date, consumer acceptance of EVs has been improving continuously with the increasing driving range. This has been an issue for a long time even though a number of studies have shown that, already today, the energy requirements of 87% of vehicle-days could be met by an existing, affordable EV (Needell *et al.*, 2016). Even though some surveys have shown that first-time drivers could be more interested in buying an EV, other polls such as Koetsier (2017) showed that acceptance of this technology even by millennials is far from guaranteed. Despite that, the tendency of millennials to favour shared services and to demonstrate preference towards access over ownership is likely to drive adoption of mobility-as-a-service (MaaS) and synergies with electric driving.

Box 10: GOGORO

Gogoro Smartscooter from Chinese Taipei has already shipped more than 35 000 scooters and has inspired the Coup scooter-sharing service by Bosch in Paris and Berlin. The business model consists of selling an e-scooter and charging a monthly subscription fee of approximately USD 25 to use the battery-swapping stations. A network of battery stations (GoStations) are part of the electricity grid – for, example, working with Amsterdam to fully tap this potential. In Chinese Taipei, Gogoro's swapping stations are already being equipped with solar panels (Gogoro, 2018).

But even once high EV penetration is reached, the theoretical availability of flexibility needs to be corrected to individual drivers' preferences. Transport service will remain a priority. There has to be an incentive for the user to plug in as much as possible to exploit the full potential of flexibility. Individual customers participating in smart charging will then have to be ensured that a sufficiently charged vehicle is always available for their commute. Also, charging habits will not be homogeneous, for example in terms of sensitivity to price. Current travel habits, access to parking, attitudes to re-fuelling and perceptions of different EV charging options may differ (Delta-ee, 2018). Dynamic tariffs will need to be comprehensive and to provide relevant incentives for customers' participation.

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 owners (mobility and preserving the condition of the vehicle).

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 EV business model. For example, providing operation services would require the battery to act "on call" while providing sTable revenues just for being available. On the other hand, electricity price arbitrage requires repetitive charge and discharge, which greatly reduces the battery life.

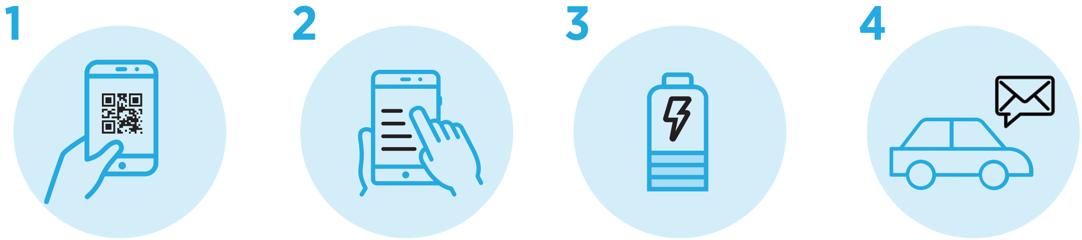
Big data and artificial intelligence

The use of digital tools can help to improve customers' acceptance of EVs and to navigate market complexity, interacting with the grid to increase renewable energy shares. Some products offered in the market already allow precisely for that. For example, the WallBox home charging solution is a smart charging system that automatically charges EVs when energy costs are the lowest, managing recharge with intuitive sense technology (Wallbox, 2018).

Even artificial intelligence (AI) algorithms could be deployed to better serve EV consumer needs. For example, Microsoft's cloud computing platform Azure, which finds patterns in data collected by sensors in the real world, interprets these data and can make decisions about maintenance or remote monitoring of different assets using AI capabilities. In Germany, Microsoft has a partnership with EnBW AG to develop smart street lights, which can collect emissions data and charge EVs. Furthermore, with ABB Ltd., Microsoft will launch the next generation of EV fast-charging platforms (BNEF, 2017d).

Schneider Electric at the EUREF campus in Berlin has collaborated with the Innovation Centre for Mobility and Societal Change to complete a micro smart grid that features AI and machine learning capacity that actively optimises EV charging. It controls charging demand to match network capacity and sends energy surplus back to the grid, based on dynamic pricing (Tricoire and Starace, 2018).

Figure 20: Functioning of SMATCH



1 **Connect to the charging station**
The user scans the QR code using the SMATCH smartphone app. Connection is also possible using a special card.

2 **Select parameters**
The user selects the charge required, and the time available.

3 **Dynamic charging**
Confirmation is sent to the user. Settings, such as the time the user has available, can be modified at any time.

4 **End of cycle**
A notification is sent when the charging cycle is complete.

Digitalisation will also enable new business models. The "charging provider" model as outlined will further develop towards an "as-a-service" model. Advancements in information and communications technology (ICT) including data management and data analytics of charging patterns will enable new functionalities like remote maintenance and management of charging stations. Services facilitating smart charging and optimising efficiency across several charging points already exist.

For instance, the SMATCH B2B solution by ENGIE, shown in Figure 20, allows the user to indicate his or her charging needs and to optimise the use of the charging point, maximising the use of local renewable energy generation and reducing peak shaving in the process. Because it reduces the total power required for recharging, SMATCH makes it possible to cut electrical infrastructure by as much as 30% (Laborelec, 2017).

Finally, digitalisation will play a key role in optimisation between transport service and the grid services, in both the planning and operation stages. Digital technologies and data analytics will make it possible to match mobility demand with power supply patterns, to be as compatible as possible and to identify the most optimal locations for charging points.

A study of Boston transport data on the best location for charging stations demonstrated that a 20-30% energy reduction potential for reaching the closest charging station without increasing the number of charging stations is possible (Santi, 2017).

In addition to finding the best places for EV charging, transport analytics derived from big data can improve the estimation of grid load and electrical cost as well as V2G. Time-of-day information is key for V2G, as generic load curves may not reveal variations in parking loads for lots that are located close to each other but that have very different profiles (Schewel, 2017).

Blockchain technology

Similarly, payment and billing for EV services as well as provision of flexibility by EVs to the grid could be further simplified by the advancement of new technologies, including blockchain. Blockchains are secured distributed ledgers enabling transactions. They operate as distributed databases that contain a continuously growing list of data records, the so-called blocks. Transactions are verified by computers run by the network's users, the so-called nodes. Therefore, no third party is needed to ensure that a transaction took place correctly. Their key advantage besides their decentralisation is the possibility to have secure and cheap transactions, including for charging.

For EV charging, the key benefits of blockchain are direct settlement (i.e., no roaming needed any more) and high interoperability and automation of services.

In November 2017 seven providers from five countries, mainly utilities, launched the Oslo2Rome experience: European transborder trips with EVs using the Share&Charge App of MotionWerk based on blockchain technology. Share&Charge is a German-based initiative with 1 200 public and private stations equipped with this solution. It is evolving from business-to-customer (B2C) towards B2B and a broader public charging network solution, enabling service providers to access the product and add it to their own toolbox.

This technology also can be used for customer-to-customer (C2C) charging solutions: the sharing of a private charger when not in use with someone else for a fee. This would require hardware for home plugs with a functionality to connect to the blockchain (a current pilot between MotionWerk and WallBee), as home charging today is done with simple plugs that, unlike public charging, are not equipped with a software back-end that verifies the identity of the user, establishes a connection and provides permission to charge.

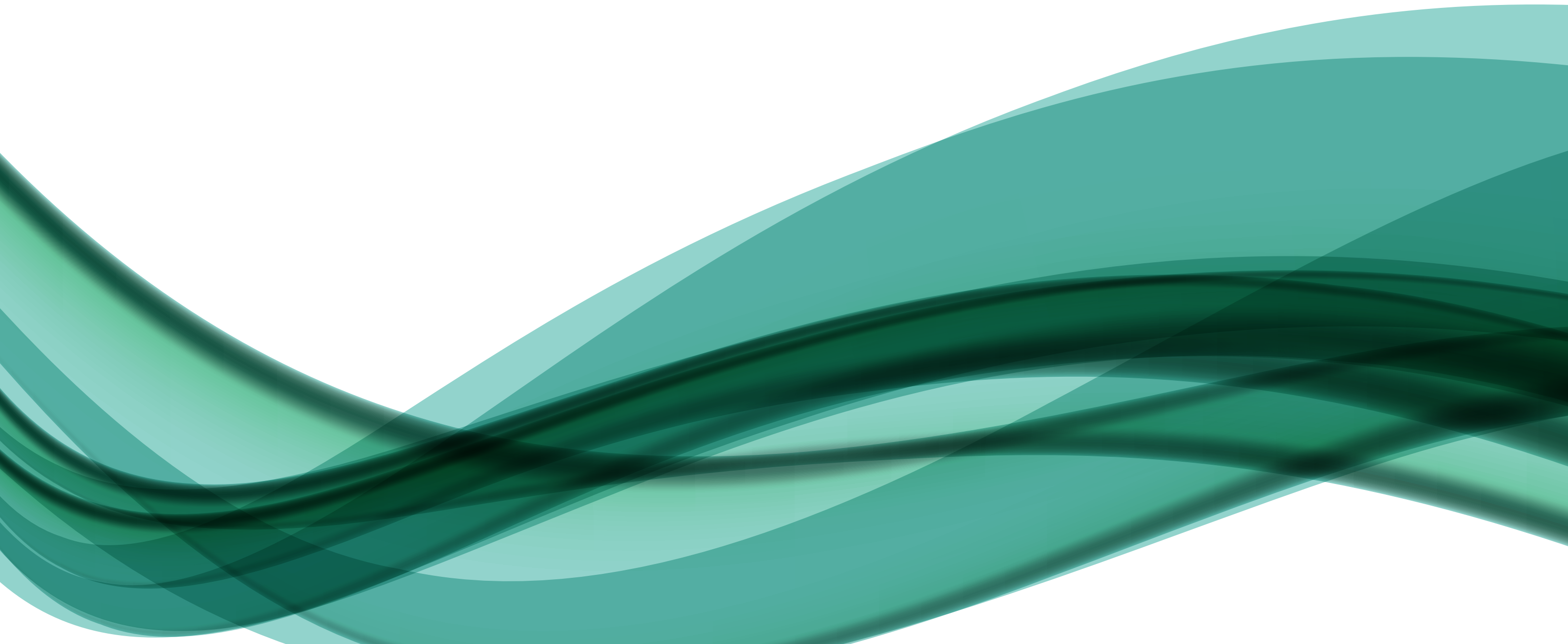
For charging and roaming, there is potential for blockchain-based solutions to disrupt or at least affect the platform-as-a-service (PaaS) model. Blockchain could facilitate smart charging and V2G by connecting different parties and facilitating monetary transactions between aggregators and customers (real-world transactions take longer and charge higher fees) through a form of open-source standards, replacing proprietary solutions being developed today. In the Netherlands, IBM, TenneT and Vanderbron are exploring the use of blockchain technology in smart charging to provide grid services (Box 11).

Box 11: TENNET AND VANDEBRON TEST IBM BLOCKCHAIN FOR SMART CHARGING

The transmission system operator TenneT has launched several projects to test the use of blockchain in managing its networks. TenneT uses IBM's permissioned blockchain platform built on the Hyperledger framework, which is implemented in various sectors including financial services, supply chains and health care.

The project in the Netherlands with the green energy supplier Vandebron is investigating the use of customers' EVs to make available flexibility to help TenneT balance the network at times of peak demand. The blockchain enables connected EVs to participate by recording their availability and their action in response to signals from TenneT. When a power increase is needed on the grid, EV charging is stopped briefly and the vehicle owner is compensated for the interruption (Engerati, 2018).

Slow charging will remain important for renewable energy integration despite the proliferation of fast charging, even after the introduction of MaaS and autonomous vehicles between 2030 and 2050. Digitalisation and standardisation will make it possible to go beyond simple time-of-use charging for EVs. Enhancing EV use, first with automated V1G and then increasingly V2X applications should also boost synergies with renewables.



4. BUSINESS MODELS AND REGULATORY OUTLOOK

Extensive EV adoption calls for new business models to develop EVSE (electric vehicle supply equipment). This section presents an overview of the current strategic positioning of actors in e-mobility, with a focus on the infrastructure.

4.1 E-mobility market actors

The e-mobility market includes the following segments:

- EV sales: while most light-duty vehicles are sold via leasing, public procurement needs to be considered for public transport means such as buses.
- Mobility services: these services include e-car sharing, intermodal transport, fleet management, electromobility service provision and, increasingly, collection and analytics of data from drivers, fleet managers and charging stations.
- Electricity sales to power EVs: this includes electricity retail sales as well as re-selling by charging infrastructure providers.
- Installation and maintenance of charging infrastructure.
- Charging station operations (smart charging / data management / billing).
- E-roaming: this is key for interoperability of charging services as well as regional/national charging independence.
- Advanced grid services such as aggregation and V2G (emerging).

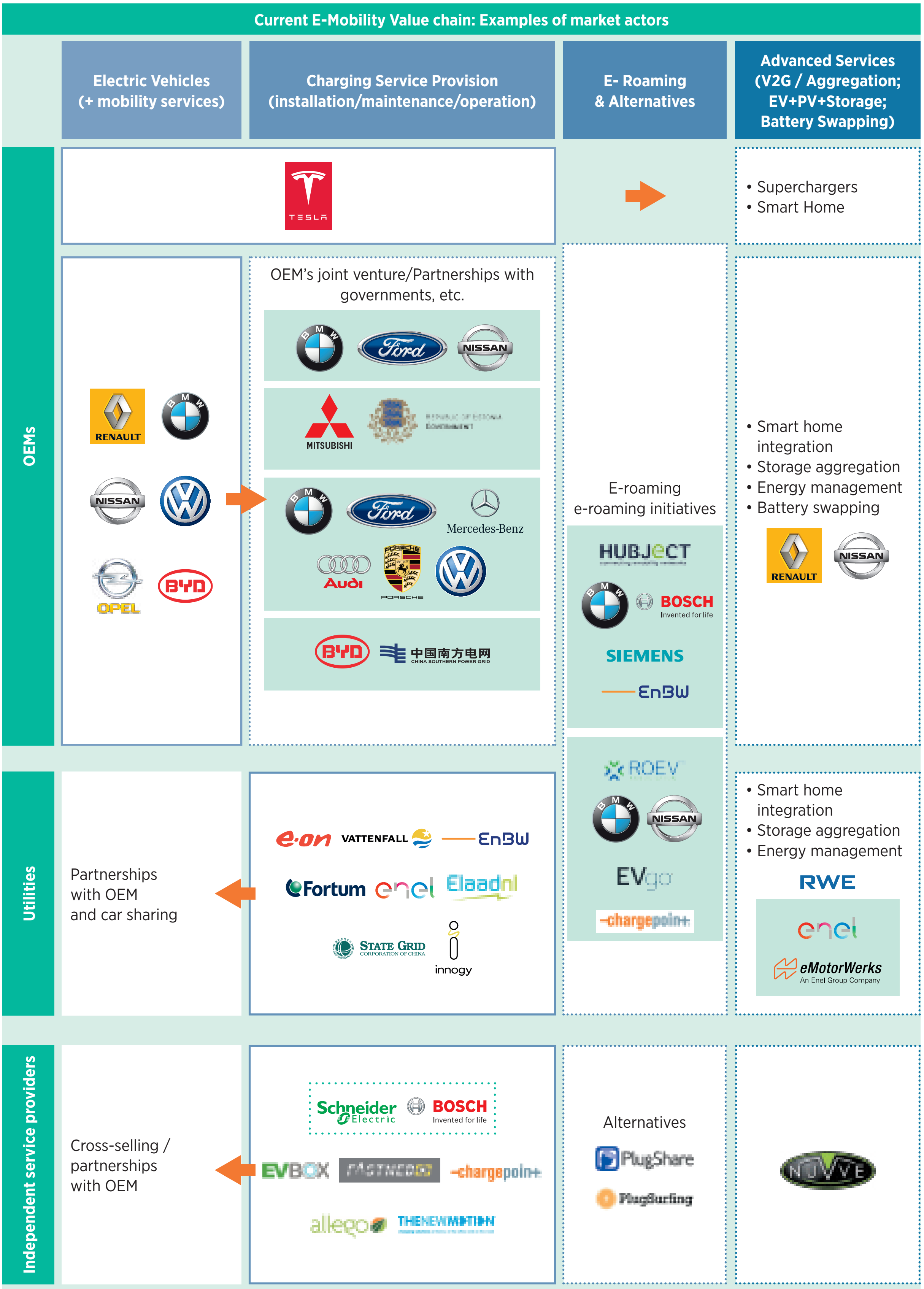
Many traditional as well as new actors from both the mobility and energy sectors are active in this emerging market. In addition to Tesla – with its vision of an integrated mobility company stirring change in the sector – new independent providers include e-car-sharing service providers (*e.g.*, Zen Car and BlueIndy by Bolloré), dedicated charging station developers, operators, data managers, e-roaming platform providers, as well as providers and aggregators of advanced grid services.

Auto manufacturers are looking for new ways into the e-mobility market and are enhancing trust in the product by focusing on reducing range anxiety. Energy utilities are looking not only to supply charging points with electricity but also for alternatives to selling "kilowatt hours-only" as they assess a shift towards charging infrastructure installation and operation, and the provision of new smart energy services. Even energy companies from the oil and gas sector are preparing for a shift towards sustainable mobility.

Across-the-value-chain partnerships among these actors are increasingly typical for this market. They look for viable business models across this value chain, capturing and providing value to the customer. The most important types of business models (Laurischkat *et al.*, 2016) and examples of market actors active in each domain are summarised in Figure 21.

The most developed business models are EV sales accompanied by mobility and charging services, as detailed in Annex 3.

Figure 21: Overview of strategic actors positioning in the e-mobility value chain



Note: Logos provided by companies. This does not constitute an endorsement or recommendation of any product or provider by IRENA.

4.2 EV-grid nexus business models

Several business models on the EV-grid nexus are being developed but are not yet fully commercialised or widespread, including smart energy services, EV flexibility aggregation, battery swapping and second-life battery use.

Smart energy services provider and aggregator

The business model of monitoring and controlling large number of resources together by aggregating them and selling their energy and/or capacity in the wholesale or ancillary services markets has been maturing for larger loads and distributed generation. However, aggregation of batteries from EVs and offering services that EVs can provide to the market have not yet been fully commercialised.

Nevertheless, interest in this model is increasing. Not only utilities, but also several large auto manufacturers as well as charging services companies are making investments in energy management and aggregation services. For example, eMotorWerks' JuiceNet platform (acquired by Enernoc, which is owned by Enel) can aggregate distributed storage facilities, including but not limited to EV batteries, to provide grid balancing and energy management services.

However, profitability and competitiveness of EV flexibility with other flexibility sources at the system level remains a key issue:

- First, price spreads in the system may be lowered – for example, by daytime solar PV generation – and may not rise again if there is sufficient flexibility in the system (low price spreads are expected in the German and Spanish day-ahead markets, but high ones are expected in the UK market (Schucht, 2017)).
- Second, revenues from ancillary services may not provide sufficient flexibility in all markets. Unlike the high estimations from pilot projects mentioned in section 3, studies from other markets may reveal much lower values. For instance, the calculation for Germany was based on a market volume of primary and secondary control of EUR 265 million for 2015, assuming 10 million EVs with 90% availability, representing a value of EUR 29 per EV per year. Notably, the demand for these services is currently limited to 660 MW, and these 10 million EVs would represent an approximate volume of 30 000 MW, thus pushing the prices even lower.
- Finally, EVs will compete with other types of decentralised flexibility such as demand-response resources, and with the used EV batteries themselves. Second-life EV batteries will be inexpensive and are already being deployed by automakers today.

The EV case may be more powerful at the local level, leading to potential minimalisation of low- and medium-voltage grid extension projects. However, this potential business case would need to be monetised for EV drivers and service providers. As mentioned above, this is currently not the case as local flexibility markets for mitigating congestion in distribution grids are missing.

Different business models are being trialled, with different actors seeing synergies with their expertise in different segments of the EV-grid nexus.

Unidirectional V1G could be handled by a charging point manager. If it were performed remotely, this could be done via a software-as-a-service (SaaS) structure, which could manage numerous charging points and other loads on a site. Alternatively, it can be implemented locally as within the charging infrastructure (*e.g.*, local EV-PV synchronisation).

V2G and second-life batteries operation require an aggregator. The original "niche" energy services provider and aggregator model will develop into an energy services platform provider, combining multiple VGI revenue streams and other energy products and services. Tailor-made combining of smart energy services / home and building energy management (smart charging, V2X) with V2G as part of a larger portfolio of aggregated distributed energy resources as well as second-life batteries will be commonplace, rather than a focus on a specific application as occurs today.

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. By connecting the EV to the

Jedlix platform, Jedlix can coordinate user charging preferences and establish a live connection with the EV, making sure they are charged smartly. Depending on the charging preference, each EV can provide either positive or negative control reserves. 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).

The current VGI is based largely on the provision of charging management software from developers of proprietary solutions (like AutoGrid or Nuvve) to utilities and fleets, sometimes operated by OEMs. The energy services platform provider model is no longer B2B but integrates the software and provides a spectrum of B2C services. The case studies of Enel and Nissan (Box 12) illustrate this emerging business strategy from the utility and the OEM perspectives, respectively.

But energy services platforms also may be integrated into other platforms and by other actors from other sub-sectors. For example, smart building "as-a-service" integrating energy management is gaining traction, and collecting data from occupants, aggregation and VGI back to the grid could be the next step, even if not the current focus. This space is currently dominated by electronics giants (Schneider Electric, Siemens, Panasonic). Siemens is using its building automation system Desigo in a research project integrating EVs into the energy management of the building (Siemens, 2017).

Box 12: FUTURE ENERGY SERVICES PLATFORM PROVIDERS: ENEL AND NISSAN STRATEGIES

In addition to developing charging infrastructure and bundled offers for home and public charging, **Enel** has invested in the development of an accessible DC V2X home charging station that charges and discharges at 10 kW. Enel has participated in various pilot projects – for example, in the pilot with Nissan in the UK they have played the role of electricity supplier at the charging point, charging software provider as well as aggregator.

In this pilot, EV clients received compensation in the form of a reduction in their electricity bill in exchange for provision of grid services, and, thanks to smart energy service, they locally optimise their consumption by increasing self-consumption of their locally generated solar energy and saving on the network charges. Enel integrated the purchased V2G power into its larger aggregated ancillary services portfolio, thus creating a "buffer" for uncertainties due to possible deviations in the schedules of individual vehicles, without directly controlling them. Enel is paid by the transmission and distribution system operators and shares the value with the client.

The JuiceNet platform by eMotorWerks – which Enel recently acquired through a subsidiary Enernoc (Enel, 2017) – will further improve the company's capabilities to provide smart energy services (EV-PV-storage). It can schedule EV charging when electricity from domestic solar rooftop systems is most abundant. Furthermore, through JuiceNet, EVs, V2G charging stations and other storage facilities also can be used to respond to network signals, aggregating charging and discharging activities to balance electricity flows in the grid when needed.

The automaker **Nissan** also eyes valorisation of aggregated flexibility as an additional revenue stream. In January 2018 Nissan launched a new solar generation and energy storage system for domestic use in the UK (Nissan, 2018). The automaker claims that its solution will allow UK homeowners to increase the rate of self-consumption from on-site PV and cut energy bills by up to 66%. Over 880 000 UK homes already have solar panels and the market is growing. This new product is a further extension of xStorage Home that Nissan developed in partnership with Eaton with second-life EV batteries.

In October 2017 Nissan announced a partnership with OVO Energy to launch a new offering combining the VNet capability of OVO with Nissan's xStorage Home system to develop an OVO SolarStore and a V2G offering for private customers buying the latest Nissan LEAF (OVO Energy, 2017).

Second-life storage applications

An alternative to recycling used EV batteries is reconditioning them and reusing them in stationary applications. Second-life battery solutions could also provide energy storage services. An EV battery needs to be replaced when the capacity declines to 70-80% – that is, when it is no longer sufficient for daily mileage but is still in good condition to be used as an energy storage system.

This offers a lifetime extension of up to 10 years for the battery, at a compelling price already today, believed to be around EUR 150 (USD 180) per kWh (Reid, 2016). Depending on the application, it can be used for grid-to-battery (G2B) pre-charging during low price periods and battery-to-grid (B2G) discharging during high price periods. For comparison, second-life batteries from the Renault Zoe can provide the same power as two Tesla Powerwalls, and at a much lower price.

Pros and cons of using second-life batteries for stationary storage are summarised in Table 14.

In addition to pilot projects, a number of OEMs have started exploiting the re-sale of recycled batteries. Offering stationary storage allows auto companies with large battery manufacturing capacity to reduce exposure to fluctuating EV sales, reduce inventory, increase manufacturing utilisation rates and monetise the battery after the initial use. Several products for residential customers (smart home optimisation) based on second-life batteries are already commercially available, while more advanced applications are in demonstration phases (Table 15 and Box 13).

Table 14: Pros and cons of second-life battery storage

Advantages	Drawbacks
· Additional monetisation of the battery after it served the main purpose in an EV · Savings on manufacturing new battery cells · Delay in recycling a battery with 70% remaining capacity, which is potentially wasteful, postponing related regulatory liabilities	· Lower performance and remaining cycle life as a battery degrades overtime due to wear and tear · EV batteries that have been in use for 10 years or more could be technologically obsolete, making them more suitable for recycling rather than repurposing them for second-life use

Table 15: Examples of secondary storage products and demonstrations by automakers

Automaker	Project description	Location	Application
BMW and Bosch	Projects of Second Life Batteries Alliance with Vattenfall	Hamburg	Support to fast-charging stations and VGI
BYD	Sale of both new and recycled batteries	China, Australia	Back-up power for telecom tower, solar-powered street lamps and low-speed EVs
Daimler, The Mobility House and GETEC	13 MWh project of 1 000 battery packs; another 15 MWh project under construction	Germany	Aims at ancillary services provision
Nissan	Back-up power for Amsterdam Arena using 148 packs from Nissan LEAFs (with Easton and The Mobility House); xStorage Home possible with second-life batteries	Amsterdam, Netherlands;	
UK	Behind-the-meter optimisation		
Renault	E-STOR systems by British energy solutions provider Connected Energy, using Renault's batteries; trial with Powervault for solar-equipped customers	UK	Utility-scale application; smart home applications

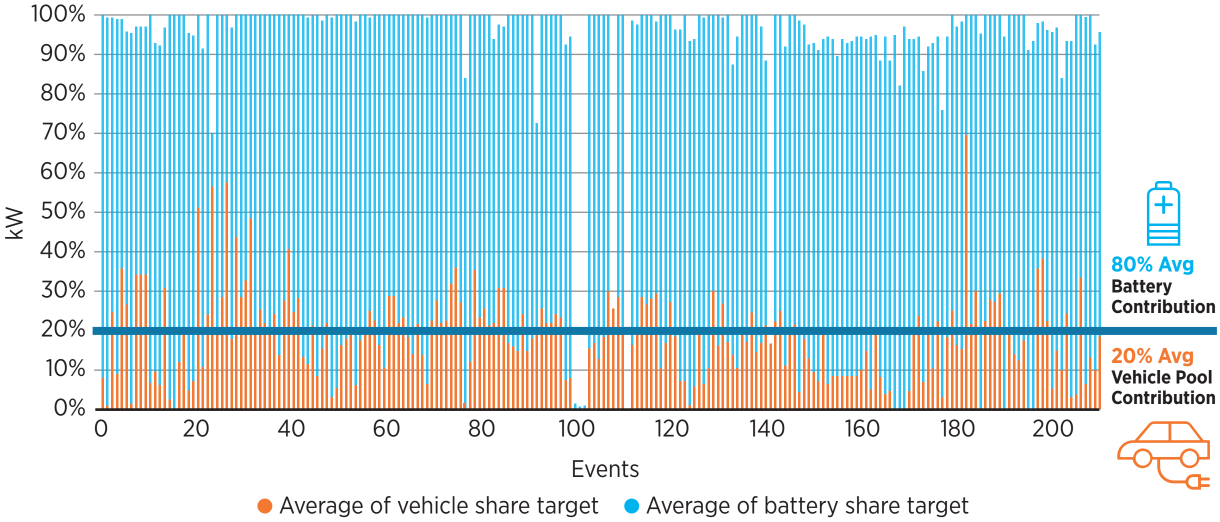
Based on Holder, 2018a; Lambert, 2016; Engerati, 2017; Renewables & Environment, 2017.

Box 13: CHARGEFORWARD PROJECT ON SECOND-LIFE BATTERY STORAGE

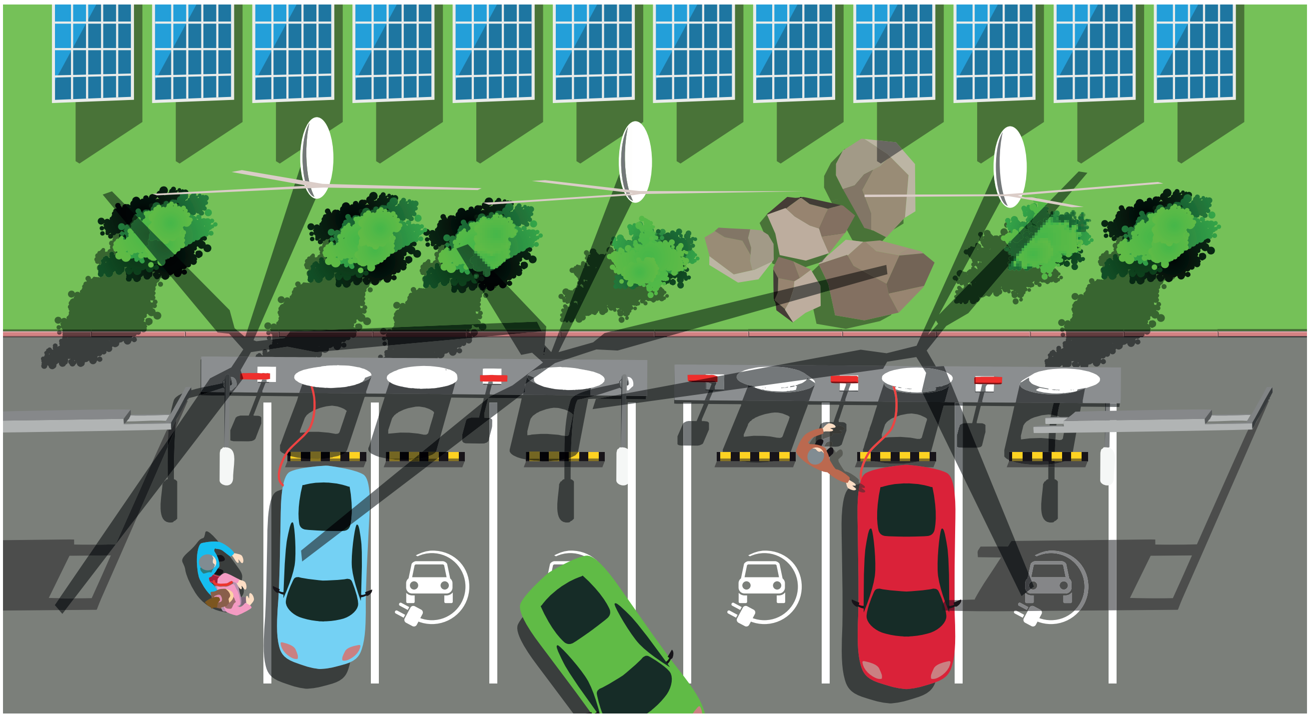
The ChargeForward project took place between 2015 and 2016 and involved Pacific Gas & Electric (PG&E) and BMW in the San Francisco Bay Area of California. The goal was to demonstrate the potential for EVs to participate in demand-response events. For that, BMW was required to provide 100 kW of grid resources to PG&E when called upon through a combination of delayed charging of 100 BMW i3 vehicles in San Francisco and drawing electricity to the grid from a second-life stationary battery system built from reused EV batteries.

The programme proved the successful dispatch of the BMW vehicles in 209 demand-response events. The vehicles contributed to 20% of the target kW reduction, and the batteries provided the remaining 80% (Figure 22) (BMW and PG&E, 2017). In the second phase of the programme, BMW has been developing the capability to align EV charging with renewable energy generation by using predictions from PG&E (Pyper, 2018).

Figure 22: BMW and PG&E project: Vehicle performance from target (100 kW)



Source: BMW and PG&E, 2017.



Battery swapping stations could be used in similar fashion with a full range of applications. Studies show that although the charging behaviours of battery swapping stations will be affected greatly by the multiple battery swapping demands of EV fleets such as taxis, which would swap batteries several times per day, growing EV fleets and battery swapping stations could limit load fluctuation and peak-valley load difference (Rao *et al*., 2015).

4.3 Regulation for vehicle-grid integration: Electricity markets

The barriers to EV adoption are progressively lowering as technology costs fall sharply. However, deploying and scaling EV charging infrastructure equipped for smart interaction with the electricity grid will remain key for the EV revolution as well as for maximising the synergies with VRE-based power systems. To bring new VGI business models from pilots to full deployment, smart energy service providers and aggregators will need to be able to stack value to incorporate EVs into their demand-response programmes, which could be especially relevant for fleet management.

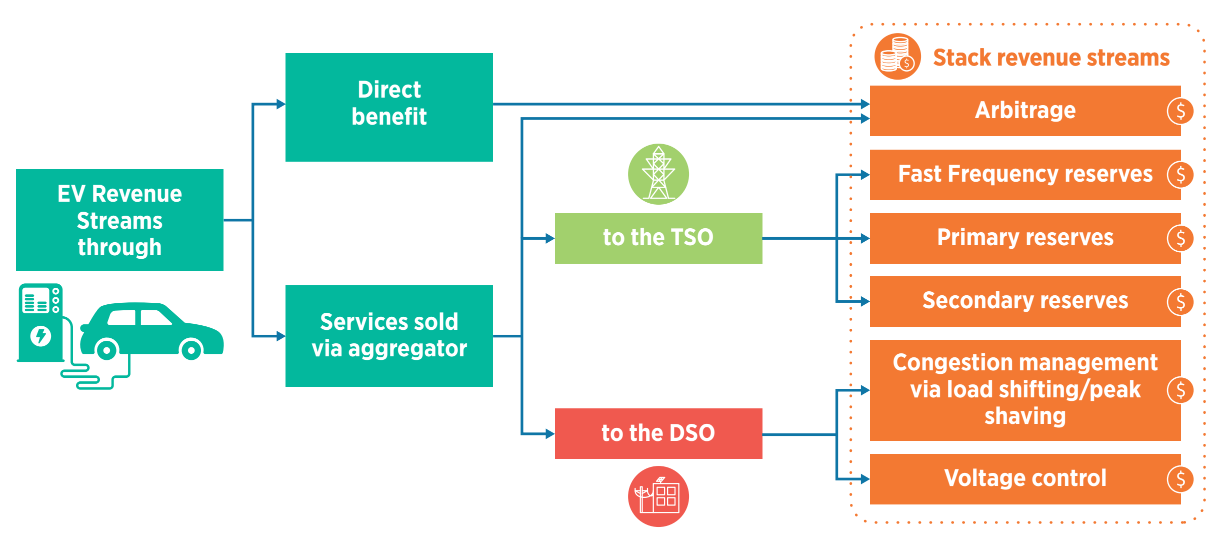
Market design and regulation for vehicle-grid integration

Smart charging will not "just happen" without the right incentives in the form of dynamic price signals, and V2G will not materialise without the possibility to "stack revenue" from multiple revenue streams, providing flexibility at both the system and local levels, as explained earlier in Figure 12 and displayed in Figure 23.

This will not happen without well-functioning electricity markets. Competitive wholesale and retail markets are not always in place today, even in the emerging e-mobility markets. In some countries, wholesale electricity markets exist, but competitive balancing/ancillary services markets and retail markets are often missing – that is, they are still regulated services executed centrally by a transmission system operator.

Double levies for V2G charging – that is, fees for charging the vehicle and fees for injecting power to the grid – should be avoided. Taxes and grid charges should be applied only to the net energy transferred for the purpose of driving.

Figure 23: Possible EV revenue streams that can be stacked



Adapted from Chase, 2016; Bach Andersen, 2019.

Aggregator business models facilitate the use of EVs as a source of flexibility. In order for EV power provision services to be viable at the wholesale level (for example, providing peak shaving and ancillary services), capacities of at least 1 MW to 2 MW have to be traded. This would require the aggregation of around 500 EVs.

Even where markets are in place, their design will need to develop, and regulation will need to be adjusted to provide incentives for valuation of EV grid services, including:

- Adjustment of market thresholds and access conditions for different wholesale segments: even in markets that explicitly allow aggregation access, minimum capacity and availability requirements for major grid services remain designed for large-scale power plants.
- Avoiding double charging of storage for the grid that penalises V2G as well as second-life batteries: payment for injection to the grid has already been recognised as a barrier by EU legislators, and the so-called Clean Energy Package (CEP) proposes to remove it.
- Outdated regulation prohibiting the resale of electricity from the grid without a supplier should be updated to account for EVs.

Allow EV batteries to provide different services to the power system, making stacking of services and revenues possible.

At the distribution level, local grid operators often are not allowed to manage congestion in their grids in a way other than by reinforcing the copperplate. Investment in smart grids and smart meters will be of key importance, even though it has not been taken up in all parts of the world yet. The development of local flexibility markets is necessary to put a monetary value on the contribution of smart charging to distribution grid optimisation and the removal of distribution bottlenecks. Except perhaps for niche applications, this is currently not the case in virtually any market (but the CEP also proposes addressing that). Distribution system operators need to be given incentives to use EV chargers as distributed energy resources instead of building new lines / transformer capacity.

Eventually, EV drivers could be able to provide flexibility to the wholesale/balancing markets as well as at the distribution level. Local price signals and locational information in bids would enable that.

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.

Dynamic pricing plans that incentivise smart charging and synergies with VRE

At the retail level, prices are not always allowed to fluctuate according to supply and demand in the system. This is not only a technical but also a politically sensitive issue in countries that regulate electricity prices, sometimes maintaining them below market value. Even if that is not the case, “fixed” rates are often more popular even in liberalised retail markets as they are easy to understand by consumers. However, with flat prices there is no incentive for smart charging whatsoever.

Pricing/rate plans that incentivise smart charging are a good practice that has already been introduced in several countries. These plans basically classify EVs as a separate load category. Usually the price difference between high-peak and off-peak periods is greater than those offered in traditional time-of-use tariffs. The goal is to ensure that EVs are charged during off-peak times and do not contribute to peak demand. A number of utilities, mainly in the US, have adopted EV home charging tariffs, offering charging rates up to 95% lower at night-time compared to daytime (BNEF, 2017e).

Some utilities/retailers also have started offering “green EV charging” plans to capitalise on the fact that 28-40% of EV owners also have home solar, compared with about 1% solar penetration among the general population (Shahan, 2017). For example, Minnesota-based Great River Energy allows member customers to fuel their EVs with 100% wind energy at no additional cost above standard and off-peak rates (Deloitte, 2017). OVO Energy in the UK offers EV owners 100% renewable electricity for both their vehicle and their home (OVO Energy, 2018).

The British regulatory agency Ofgem also has launched a debate on adjusting regulated network charges for households and smaller businesses wanting to consume a lot more power at peak times, with the proposed reform for 2022 (Holder, 2018b).

Standardisation

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.

For these reasons, standardisation is critical to facilitate penetration of EVs and charging infrastructure and their interaction with the power grid. Several norms were published at the global level by the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) and transposed in supra-national and national versions. Figure 24 provides a synthesis of the main international norms and their application domain for EVs.

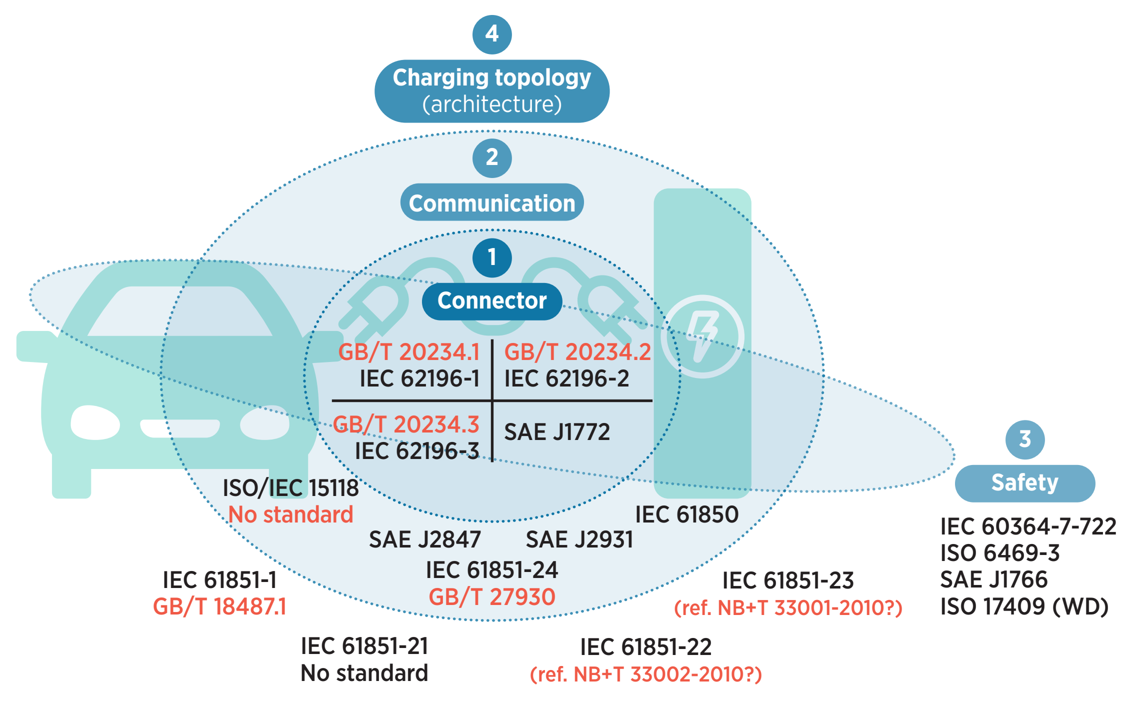
The IEC 61851-3 series, published for light electric vehicles, focuses on the requirements of AC and DC conductive power supply systems, battery swap systems and communications. The work by the IEC, ISO and their local representatives is a continuous activity. The existing norms are updated regularly to follow the evolution of electric mobility, and new norms are in preparation. In addition to the official standards, several protocols have been (or are currently being) developed by private actors that try to build industrial standards through partnerships. This often makes it possible to obtain faster standardisation, even if several industrial standards might co-exist. This is particularly the case for communication between the different actors of a charging station.

To implement unidirectional smart charging (V1G), charging stations should include the following functions:

- A charging system allowing a certain level of control including variation of charging current: from the programmable relay (local open-loop control) to the charging point with current modulation facility, including a simple charging point with Open Charge Point Protocol (OCPP) communication (charging station to get signal on grid capacity) and remote start/stop.

  While many of today's charging stations are not able to vary the charging current, the implementation

Figure 24: Overview of main international norms related to electric mobility

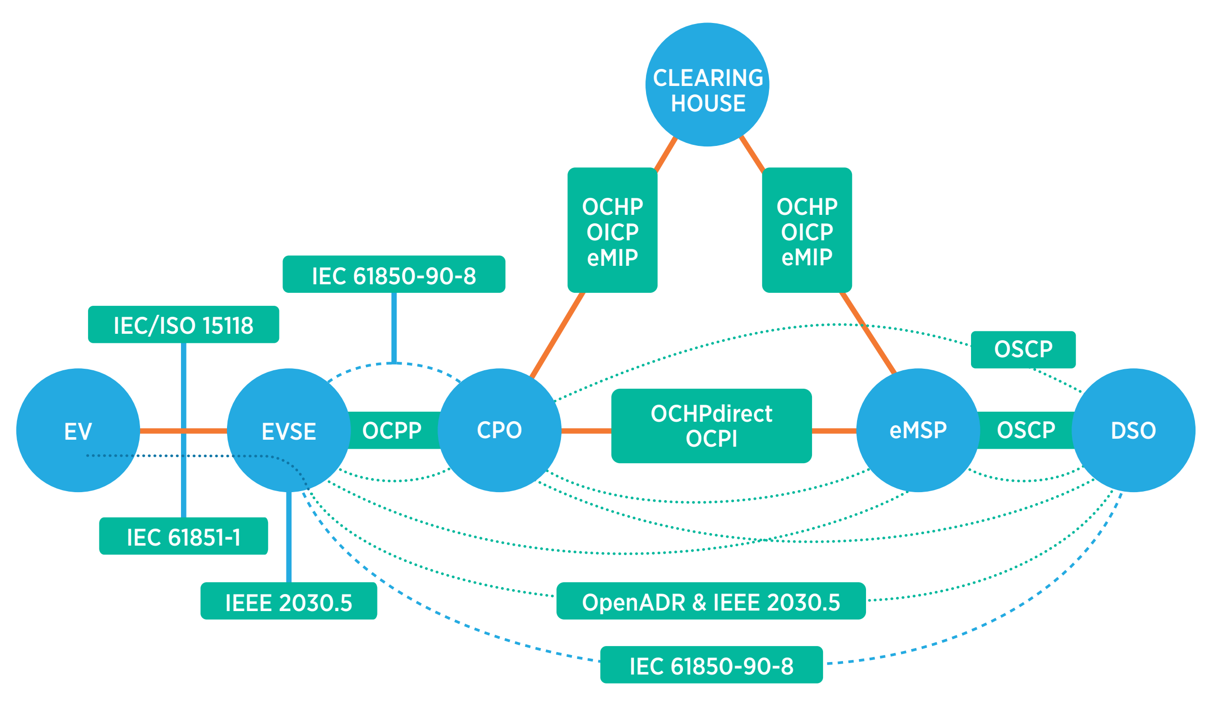


of OCPP – which regulates the exchange between the charging station and the charging station operator – should help overcome that. In addition, communication might be suiTable between the smart charging operator and the EV user, some energy meters and an aggregator. OCPP and the other most important protocols (Open Clearing House Protocol (OCHP), Open InterCharge Protol (OICP), Open Charge Point Interface (OCPI), Online Certificate Status Protol (OSCP) and Open Automated Demand Response (OpenADR)) are mentioned in Figure 25, with their position in the communication chain. They are combining with several official norms.

- Energy measurement systems: current clamp or smart meter or other meter with automatic reading and data transfer functionalities.
- For closed-loop energy management: communication between the charging point and an energy management – local solution with standard (*e.g.*, Zigbee, Modbus, Bluetooth) or dedicated protocol, or remote solution (*e.g.*, OCPP) for control by the charging points platform.
- User interface: a local screen on the charging point, a remote web or mobile application, for the EV user and/or the site manager.

Standardisation also will facilitate the spread of V2G and V2X technology (which currently has an interface cost 3-5 times higher than that of unidirectional smart charging). Such more complex forms of smart charging require:

Figure 25: Overview of communication protocols in electric mobility



Note: EV = electric vehicle; EVSE = electric vehicle supply equipment; CPO = charging point operator; eMSP: = electric mobility service provider; DSO = distribution system operator

Source: V2G Clarity, 2017.

- Bidirectional charging stations: today only limited (dis-)charging infrastructure is commercially available (*e.g.*, Nichicon, IKS, Magnum Cap).

- Cars that can discharge (not only charge): most of the V2X initiatives are implementing an off-board solution (AC/DC converter located in the (dis-) charging point). This is since the first bidirectional (charging/discharging) communication protocol was published by the Japanese CHAdeMO Association, as an extension to its DC charging protocol which is implemented by, for example, Nissan and Mitsubishi. Standardisation work at the global level is occurring in the context of the IEC/ISO 15118 Ed2 for on-board discharging solutions (expected finalisation by 2019). CHAdeMO Association's off-board solution based on the V2H guideline in Japan is also being standardised as part of IEC 61851-23/24 Ed2 (EV conductive charging systems). On-board discharging is already in development or proposed by Renault and BYD, respectively. This would allow a broader use of V2X, since the lower-cost and more widespread AC charging points might be additionally used for discharging. This would, however, require some technical adjustments to charging solutions to make them compliant with the IEC/ISO 15118 standard and also would require EVs to carry additional components, which will be an add-on in terms of costs and weight to the vehicle.

- A standardised way to know the state of charge of the vehicle: this is currently not available, which makes smart charging and V2X more complicated. Workarounds exist, such as using a proprietary app from a vehicle supplier, but it requires deployment of an ad hoc smart charging software connector.

- IEC 63110: currently under development, this international standard defines a protocol for the management of EV charging and discharging infrastructure. It is a group of standards for electric road vehicles and electric industrial trucks that works on the normalisation of the OCPP communication standard and the compatibility of other international standards (*e.g.*, CCS, CHAdeMO).

- IEC 61850 is defining communication protocols for intelligent devices and electrical substations. It has not yet been implemented in vehicles. An update of the standard is in draft and will enable more standardised smart charging and V2X.

International acceptance of these standards will be key for the spread of this technology beyond the most developed European and US markets, where most of the new charging stations are already being purchased with this technology. For example, in the Netherlands, the partners of Living Lab Smart Charging (325 municipalities, Allego, ChargePoint, EVBox, etc.) agreed to install only smart charging-ready stations for new public stations. Older stations are progressively retrofitted to be smart. In November 2017 there were 7 500 smart charging-ready (semi-)public charging points, with tenders for an additional 7 000 smart charging-ready points (Living Lab Smart Charging, 2017). In other markets, this is mostly not the case.

In other parts of the world (*e.g.*, India), implementation of global EV standards (or national standards based on global standards) will be required (Ghatikar *et al.*, 2017).

If the necessary capabilities are increasingly integrated into charging stations and into the vehicles, and if common actions to set standards come into place, smart charging will turn from promise to practice by 2030.

5. E-MOBILITY OUTLOOK

This section provides an overview of the electric vehicle market, its evolution, and the transport trends that affect the ability of EVs to contribute to renewable energy integration.

Plug-in EVs include any motor vehicles that can be recharged from external sources of electricity:

- The full battery-electric vehicle (BEV) depends solely on electricity from the grid.
- The plug-in hybrid (PHEV) combines a rechargeable battery with an internal combustion engine motor.
- The range extender (REEV) is at first an electric car; in the absence of charging infrastructure, a small combustion engine can be used to charge the battery and extend the driving range. PHEVs and REEVs are often considered as a single category.

5.1 Cost and competitiveness of EVs

Until now, the most crucial factor that has led to a substantial cost decrease for EVs in the last few years is the decline in battery pack costs. Improvements in battery technologies have reduced the average price of battery packs from USD 1 000/kWh in 2010 to around USD 200/kWh in 2017 (UCS, 2017). Analysts expect a further decrease in price to levels of USD 100/kWh in 2025 (McKinsey, 2014), which in turn would result in EVs being competitive with ICE vehicles. As a rule of thumb, this total cost of ownership parity between EVs and conventional gasoline vehicles will be reached at battery prices of around EUR 175/kWh (UCS, 2017).

Another noTable factor that has helped to reduce EV prices over the years is the increasing variety of models being offered in the market. Whereas in 2010 early customers interested in EVs could choose among only a few limited options – such as the Nissan LEAF, the Citroën C-Zero, etc. – today the range of models is more extensive, providing buyers with different choices of vehicles in terms of price, driving range, power train, battery pack and consumption. As more models enter the pool of choices, the market has become more competitive and prices for EVs have gone down.

EVs will need to achieve near parity on a first-cost basis with ICE vehicles and to provide sufficient amenities (such as driving range and recharging convenience) so that consumers do not consider them inferior to or comparable to ICE vehicles.

Total cost of ownership comparison

The total cost of ownership (TCO) assesses all costs incurred by a vehicle owner over its lifetime. It includes the cost of the vehicle purchase, the cost of the vehicle use and the re-sale value. Every time a TCO analysis is performed, taxes and purchase incentives specific to the region of study are also considered.

Economic comparison demonstrates that both gasoline and diesel are currently more competitive than EVs for most users (depending mainly on their annual fuel consumption). A strong implementation of monetary incentives, such as tax reliefs, in a region can shift the choice between an EV and a diesel vehicle, as shown in Annex 4.

EVs will likely be at TCO parity with both fuels by 2030, depending in part on oil prices. Substantial decreases in the TCO of EVs are expected in the years to come. The exact pace of TCO parity will depend on the location, the annual distance driven and the vehicle consumption.

A further decrease in the capital expenditure (CAPEX) of batteries will be the main driver. While all other EV costs are essentially flat, battery costs are falling rapidly. In 2016 the average battery cost about USD 275/kWh. It is expected to drop to USD 100/kWh in 2025, and the most optimistic predictions put it down to USD 60/kWh in 2030 (BNEF, 2017a).

Figure 26 shows how the TCO of diesel and EVs could evolve until 2050. The graph, although illustrative, aims to emphasise that in the medium term (the second half of the 2020s) EVs will eventually be more competitive than diesel vehicles even without subsidies and taxes. If that is the case, EVs could reach a global fleet penetration of 7% (IEA, 2018a).

The continued decrease in TCO is supported by the same trends described earlier and can be strengthened by two more observations. On the one hand, because of new mobility business models oriented to car-sharing practices that are expected by 2050, there will be a shift from privately owned cars to shared vehicles (see section 5.3). This will inevitably increase the EV utilisation rate to ranges from 40 000 to 55 000 km per year, and will in turn increase the EV's fuel cost savings in comparison with a diesel car driving the same yearly mileage.

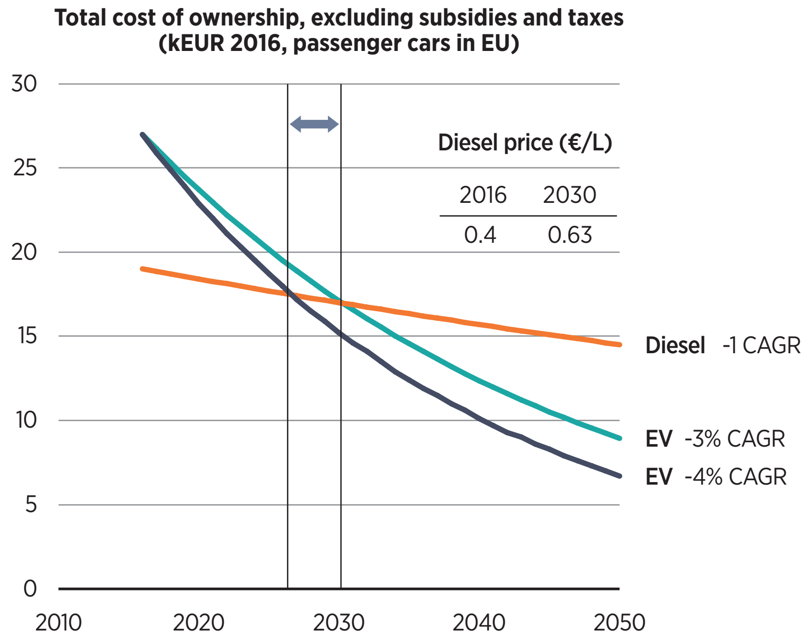
On the other hand, an unknown variable is how quickly the TCO of EVs will go down in comparison with diesel vehicles. This point could be influenced by the recent and upcoming wave of countries setting bans on fossil fuel vehicle sales by as early as 2025 (in the Netherlands) or by 2030 to 2040 (in France and the UK) (Table 2).

A case study of the 2030 TCO outlook for EVs and diesel passenger cars that are most common in Europe can be found in Annex 4.

Evolution of vehicle-related policies

The evolution of policy incentives for EVs will depend on local conditions. Once EVs become competitive with ICE vehicles, direct monetary incentives may be less important. By 2025 to 2029, in many countries, EVs will become cost competitive even without subsidies and before taking into account fuel savings (BNEF, 2017a), decreasing the need for subsidies. Another reason for

Figure 26: Illustrative total cost of ownership (TCO) outlook for electricity and diesel-powered cars until 2050



Based on BNEF, 2017c; McKinsey, 2014; UCS, 2017.

EVs will probably reach competitiveness with ICE vehicles between 2025 and 2030 (depending on the type, location and oil prices). However, supporting policies are needed initially to bring down the fixed cost of the vehicles.

the end of incentives could simply be that governments have achieved their target objectives, thus making the pursuit of the policy incentives obsolete.

However, significant variations across regions will impact the timing of the phase-out of incentives. While sales of EVs are expected to increase rapidly in the main automotive markets, the global growth is far from uniformly distributed. Such divergences have already started to appear as pockets of growth have emerged, with significant penetration rates in countries such as China, the Netherlands, Norway and the US.

Temporary support for electrification in specific systems like islands might also be needed. Fiji and Sri Lanka already have been incentivising hybrid cars by lowering taxes on these technologies. Jamaica has considered similar incentives for EVs.

With a higher EV market share over time, revenue loss from traditional incentives – which mainly include tax exemptions and tax credits – can become significant, and governments may be tempted to rely increasingly on alternative methods of promoting electric mobility. Transport targets will probably remain of relevance for driving decarbonisation of the sector.

5.2 Outlook for batteries

Some of the main challenges that EVs will have to face in the coming decades lie with their batteries. The years 2030 and 2050 may see breakthroughs in other battery technologies than lithium-ion and in their use for grid applications.

Battery chemistry evolution will affect not only mobility aspects such as driving range but also the speed of charging (also related to grid infrastructure reinforcement needs) and the ability of batteries to provide grid services.

Despite high energy density and suitability for both mobility and grid applications (see Annex 4 for details), Li-ion technology has limitations in terms of safety and the future availability of this element (and probably also cobalt), as well as related potential cost impacts. Improving the safety parameters of any Li-ion subchemistry would in turn lead to deteriorated performance (in particular energy density). The cost can be expected to decline in the next few years. But as with lead-acid in the past, it will then reach a sTable value. Only a change in technology (as with sodium-ion for cost or redox flow for safety) can change these issues, even if Li-ion (with strong advantages today) would be hard to displace.

To address the challenges of electric mobility – such as power, distance travelled and charging time – new battery technologies are necessary. Despite ongoing major research on Li-ion, other technologies present high potential and are also being developed.

The outlook for battery technologies up to 2030 and 2050, respectively, is presented in Figure 27. While Li-on will probably remain the prevalent technology until 2030, potential breakthroughs in other technologies may lead to its replacement in the long-term horizon.

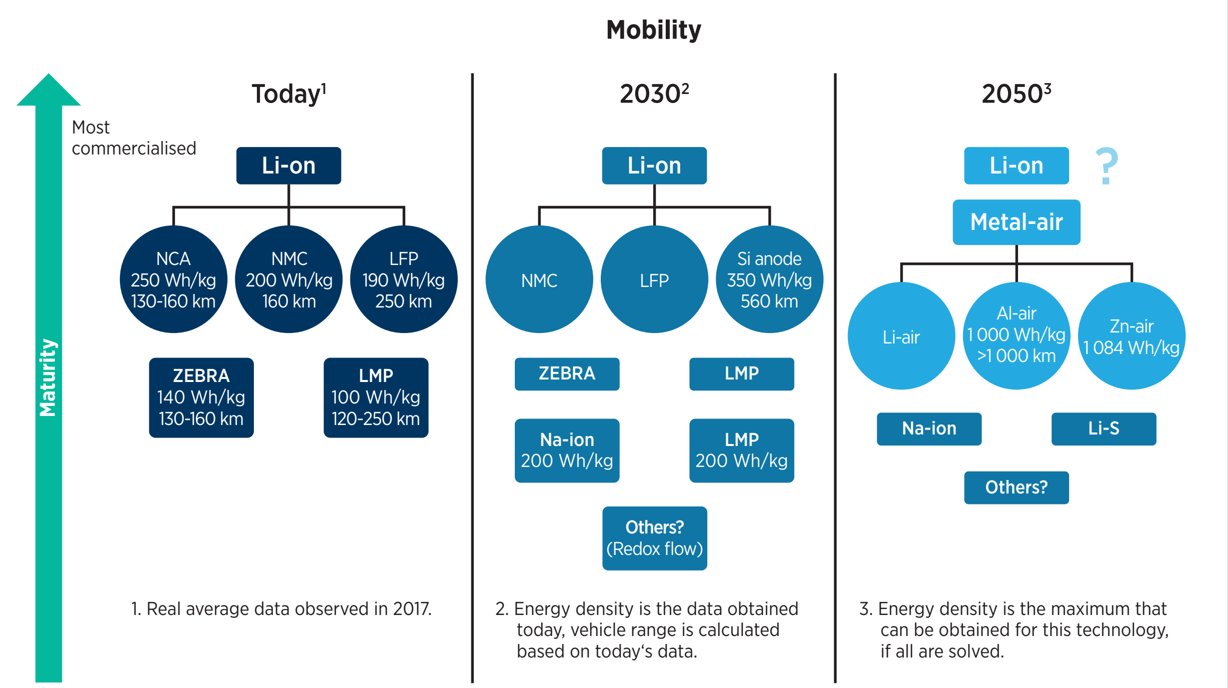
Two technologies that have already been commercialised – for example, as minor technologies in e-buses for around 10 years – are Zeolite Battery Research Africa (ZEBRA) and lithium-metal-polymer (LMP) battery technologies.

Other technologies with lower maturity levels are currently under development (only cells are sold, not systems) and could be potentially disruptive if their issues are solved, including:

- Li-ion systems with silicon (Si) as a negative electrode
- Lithium-sulphur system (Li-S)
- Sodium-ion batteries (Na-ion), which are raising interest due to the potential low cost and environmental friendliness
- Metal-air batteries including aluminium-air (Al-air) and zinc-air (Zn-air)
- Redox flow batteries for mobility applications.

Annex 4 provides more detailed description of these technologies.

Figure 27: Outlook for battery technologies compared to their maturity today



1. Real average data observed in 2017.

2. Energy density is the data obtained today, vehicle range is calculated based on today's data.

3. Energy density is the maximum that can be obtained for this technology, if all are solved.

Energy density (Wh/kg) and vehicle range (km) are noted when possible.

Predicting prevailing battery technologies for 2050 remains difficult. Nevertheless, envisaged increases in the energy density of batteries will lead to a greater battery capacity and to improvements in the amount of energy that could be stored or released in line with the needs of the electricity system. Vehicles with 200 kWh batteries (1 000 km) may turn from promise to wider practice.

5.3 Shared e-mobility: Mobility-as-a-service

Changing mobility needs will lead to the rise of business models that could transform mobility systems over the coming decades. Removing the pain points that travellers face during their journeys could prove to be a crucial opportunity for new businesses to appeal to customers. A new concept is already paving the way for these business opportunities to emerge, via a shift from an ownership-centred approach of transport to mobility options that are consumed as a service. This service-centred mobility is called mobility as-a-service (MaaS).

Mobility-as-a-service is a way to seamlessly combine transport alternatives from various providers (including shared mobility providers but beyond). MaaS goes beyond calculating the fastest path from one place to another and instead offers a one-stop shop for everything from optimised travel itineraries to payments. A MaaS offering thus consists of four complementary functionalities: trip planning, booking, payment and ticketing/billing.

However, mobility as a service is far from being achieved yet. In order to meet the mobility needs of thousands of customers, MaaS will require extensive analytics, mobility modelisation and data purchases along with the development of a comprehensive transport operators' portfolio to ensure that all users find a ride in a timely fashion. To realise this vision, the emergence of new players is essential.

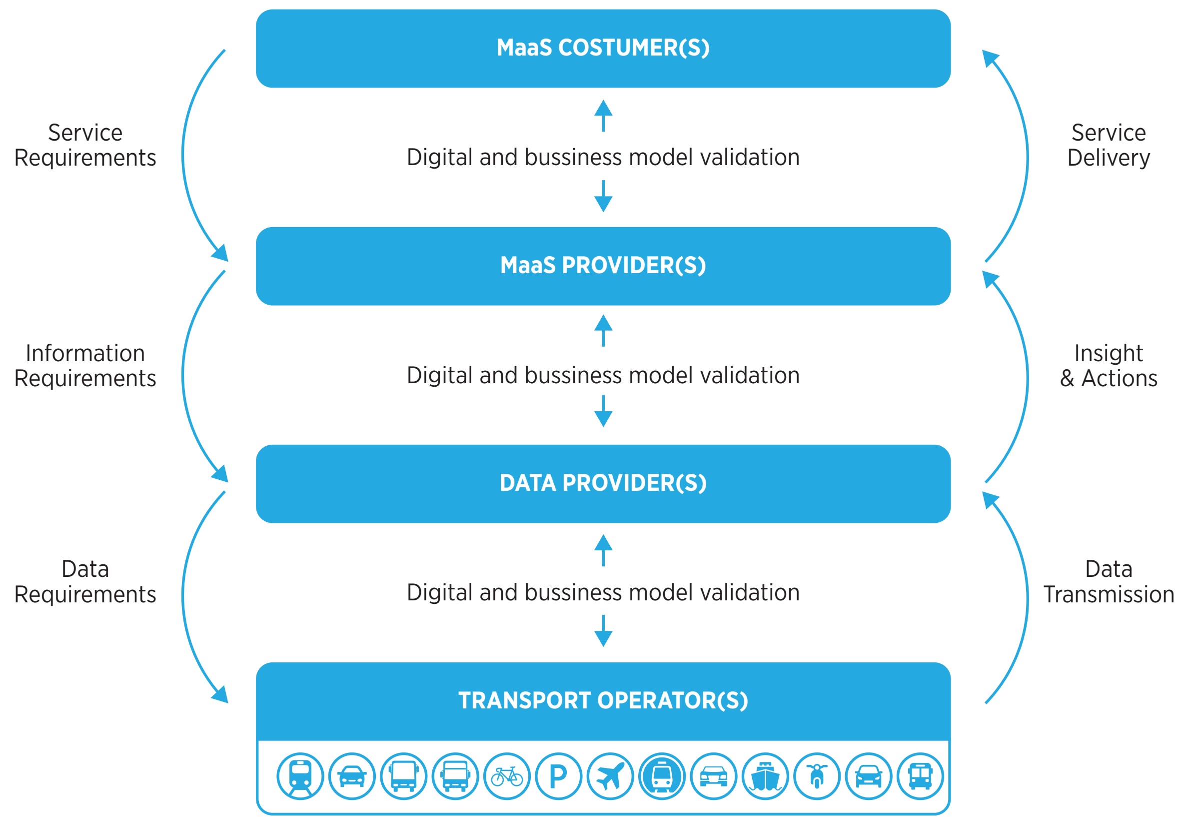
At the centre of the MaaS design are four main actors, each of them having a key role in providing the MaaS offering. These actors are the customers, the MaaS providers, the data providers and the transport operators. Although customers have progressively adopted new mobility possibilities over the last decade, and while transport operators are already in place in many countries, MaaS providers and data providers remain almost non-existent. The following section and Figure 28 clarify the value that each step of the value chain offers to the customer.

To begin with, the MaaS providers will enable customers to book and plan door-to-door trips using a single app. To do so, they will provide a software incorporating a cashless payment engine, a ticketing function, as well as a journey-planning tool. To support these services, MaaS providers will need to build a powerful analytics engine – to determine how to allocate resources at peak time, and to anticipate demand. In addition, building a large network of transport operators, both public and private, will be vital to offer solutions that best suit their customers' mobility preferences.

Making MaaS a reality would also require collecting a large volume of real-time information on thousands of customers. Therefore, data providers are needed. They will access and aggregate data from various sources, analyse them and resell them to the MaaS provider. While a MaaS provider could supposedly also play this role, the complexity of each task and the sensitivity of issues such as data privacy and antitrust laws might prevent a single player from fulfilling all these functions alone (Catapult, 2016).

Finally, and vital to any MaaS ecosystem, transport operators will supply the transport capacity to the MaaS providers. Although visible and numerous, these providers form only a part of the new mobility ecosystem. Transport operators range from public trains to bike-sharing services. These transport providers are most of what we know today. A shift in the ownership of the relationship with the commuters may be the most

Figure 28: Simplified mobility-as-a-service value chain



significant difference in the business model, with the commuters dealing with the MaaS provider rather than with the transport operator.

The new MaaS business models include integrated MaaS providers that take care of finding the best possible route according to the customer's request, book the trip and then invoice everything in one single bill. Data providers enable MaaS providers to offer truly tailored experiences and transport providers (building on fleet management as is known today).

5.4 Autonomous EVs

Technology-enabled services for ridesharing and car sharing are modelling new ways for moving groups of persons from one place to another. The electrification of vehicles and the advent of autonomous cars are expected to greatly accelerate the uptake of shared mobility and eventually MaaS.

Because the transition from private ownership to business ownership means higher mileage daily, transport providers can be expected to not simply buy the cheapest vehicles, but also to consider any that are not too expensive over the long run. As electricity will remain much cheaper than diesel or gasoline over the next decade, and as EVs emit fewer greenhouse gases and less particulate matter in a context where regulators want to ensure air quality in cities, fleet managers will most likely favour EVs over ICE vehicles.

In addition to the growth of EVs, the emergence of autonomous vehicles will boost MaaS developments. Although autonomous vehicles are not essential for the development of MaaS, they could become a powerful growth lever in the ecosystem of seamless mobility. Among the main advantages that autonomous vehicles can offer are the following:

- More autonomous vehicles would mean more time for end-users, as this would allow the passengers to focus on other tasks while "driving".

- Autonomous vehicles would make traffic more efficient, since they would be allowed to drive at a higher speed, closer to each other, while having a lower risk of accident.

- The emergence of autonomous vehicles will most likely decrease the operating expense of fleet operation, as the driver's salary represents a large part of this expense.

- Finally, the trend toward autonomous driving would help free up parking spots, as autonomous vehicles would increase the vehicles' utilisation rate, thus decreasing the amount of time they spend parked.

Evolution of vehicle DNA: Towards autonomous vehicles

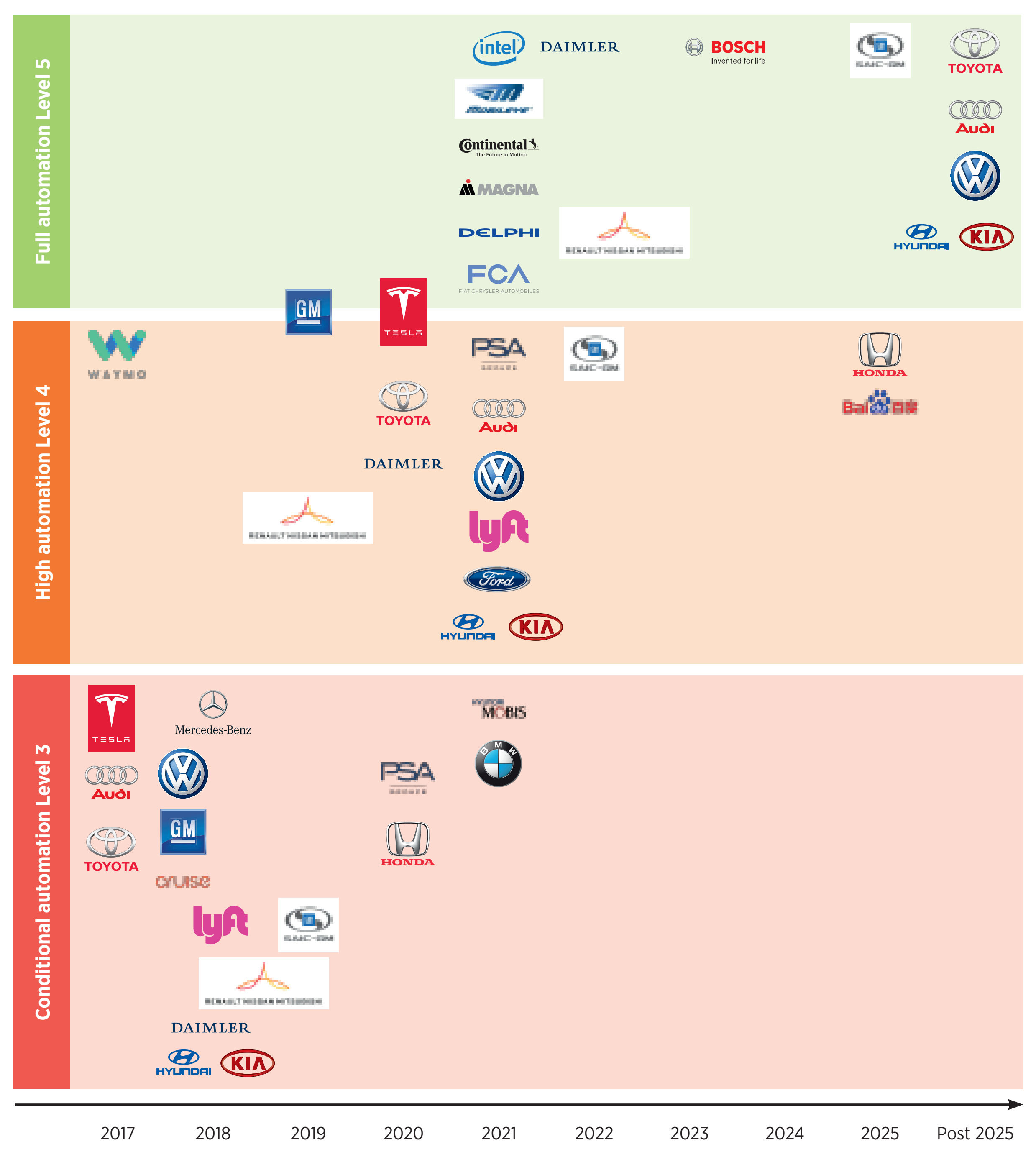
Manufacturers of vehicles, buses, trucks and to a lesser extent two-wheelers are actively developing connected cars and autonomous vehicles. Figure 29 summarises the expected timeline for autonomous vehicle introduction into markets. Daimler, for example, publicly announced a focus on the CASE (Connected, Autonomous, Shared and Electric) strategy (Daimler, 2016).

Shared vehicles make more sense with EVs because operating costs are cheaper than for comparable gasoline or diesel vehicles, which means the more mileage, the more quickly the purchase is recovered. Different degrees of autonomy, according to the classification by the Society of Automotive Engineers, include:

- Level 0 (hands on, eyes on): no active assistance system
- Level 1 (hands on, eyes on): longitudinal or transverse guide
- Level 2 (hands temp off, eyes temp off): longitudinal and transverse guide (traffic control)
- Level 3 (hands off, eyes off): takeover on request (awareness for take over)
- Level 4 (hands off, mind off): no takeover request (no driver intervention)
- Level 5 (hands off, driver off): no driver (Dyble, 2018).

The autonomous car project launched by Google, called Waymo, has already been testing autonomous cars in the city of Phoenix in the US, offering free self-driving taxi rides.

Figure 29: Expected launch times of autonomous vehicles



Updated from BNEF, 2018b.

Connected cars can communicate with the driver, the infrastructure (vehicle-to-infrastructure, or V2X[7]) or other vehicles (vehicle-to-vehicle, or V2V). By communicating with the driver, the experience is becoming more convenient for the driver, with services such as pre-heating the cars. Moreover, features for smart charging (the ability to see the state of charge of the car and to programme the charging at more suiTable moments) are also possible. V2X and V2V facilitate autonomous driving by obtaining information on the traffic and roads. There are many pilots of autonomous driving. For example, in the SCOOP project, Renault is using both V2V and V2X to enable autonomous driving by reducing traffic congestion and increasing safety. The project started in 2014, and in 2017 it entered the deployment phase with 1 000 specially equipped Renault Megane vehicles (Renault, 2017).

Regarding buses, Navya and EasyMile already are proposing small shuttles that can drive autonomously at low speed in a well-defined area. Bus manufacturers such as Daimler and Proterra also have shown interest in autonomous vehicles. Although electric and autonomous trucks are at a lower level of maturity, a similar trend may appear. For example, Embark is developing technology for autonomous trucks, and Tesla's electric semi revealed in late 2017 will also include enhanced autopilot (Tesla, 2018). Since Tesla is actively developing autonomous technology for cars, its technology also can be implemented in its trucks.

There are encouraging signs to date with regard to autonomous vehicles, with the cost of the technology expected to drop. Aptiv expects the cost of the necessary hardware and software package to decline from a range of USD 70 000 to USD 150 000 today to around USD 5 000 in 2025 because of technological developments and higher demand (Lienert, 2017). The hardware includes the graphics processing units (GPUs) to control the vehicles from inputs coming from the sensors (*e.g.*, the Tesla Model S includes eight 360° surround cameras, 12 ultrasonic cameras and radars that can "see" even during adverse weather conditions such as heavy rains). The data also may come from the infrastructure or from other cars (indications on traffic jams or accidents on the roads and maps). Fully autonomous cars need complex software typically based on artificial intelligence techniques such as deep learning.

In a future of MaaS and autonomous vehicles, with significant grid demands from the charging hubs, the need for AI-based software will increase even further. Data analytics and increased understanding of mobility will help both public and private stakeholders strategically bring this technology to the market in a way that benefits constituents, while solving key mobility challenges and optimising the grid. By leveraging hundreds of millions of trips, parking availability and restrictions, and demographic data, INRIX has identified the top markets for autonomous vehicle deployment based on current travel patterns. Using these data-driven insights to inform public planning will allow cities to proactively leverage highly automated vehicles to address key mobility and societal challenges, rather than reactively dealing with possible impacts of this technology (INRIX, 2017).

Addressing regulatory challenges and concerns of fully autonomous driving

Regulation centred on autonomous vehicles directly impacts the EV market. Because autonomous car technology is a less mature market than that of EVs or shared mobility, many governments are not yet equipped for the operation of this type of vehicle fleet on public roads.

Germany and Japan were the first countries that allowed for testing of autonomous vehicles and that enacted technical standards requiring fully autonomous systems to be compliant with traffic regulations. In the US, several states (*e.g.*, Arizona, California and Nevada) allow public road testing for autonomous vehicles (Karsten and West, 2018). China issued its first guidelines for road tests of autonomous vehicles in 2017 and its first road test licences in 2018 (Bhunia, 2018).

Liability, privacy and security concerns represent an important barrier to the implementation of autonomous vehicle technologies. Assessing liability in accidents is a particularly delicate topic for regulators. Ethical challenges may emerge when dealing with the damage

---

[7] In this context, V2X relates to information transfer from the vehicle to the infrastructure. In the charging and discharging context, V2X refers to energy transfer from the vehicle to the infrastructure.

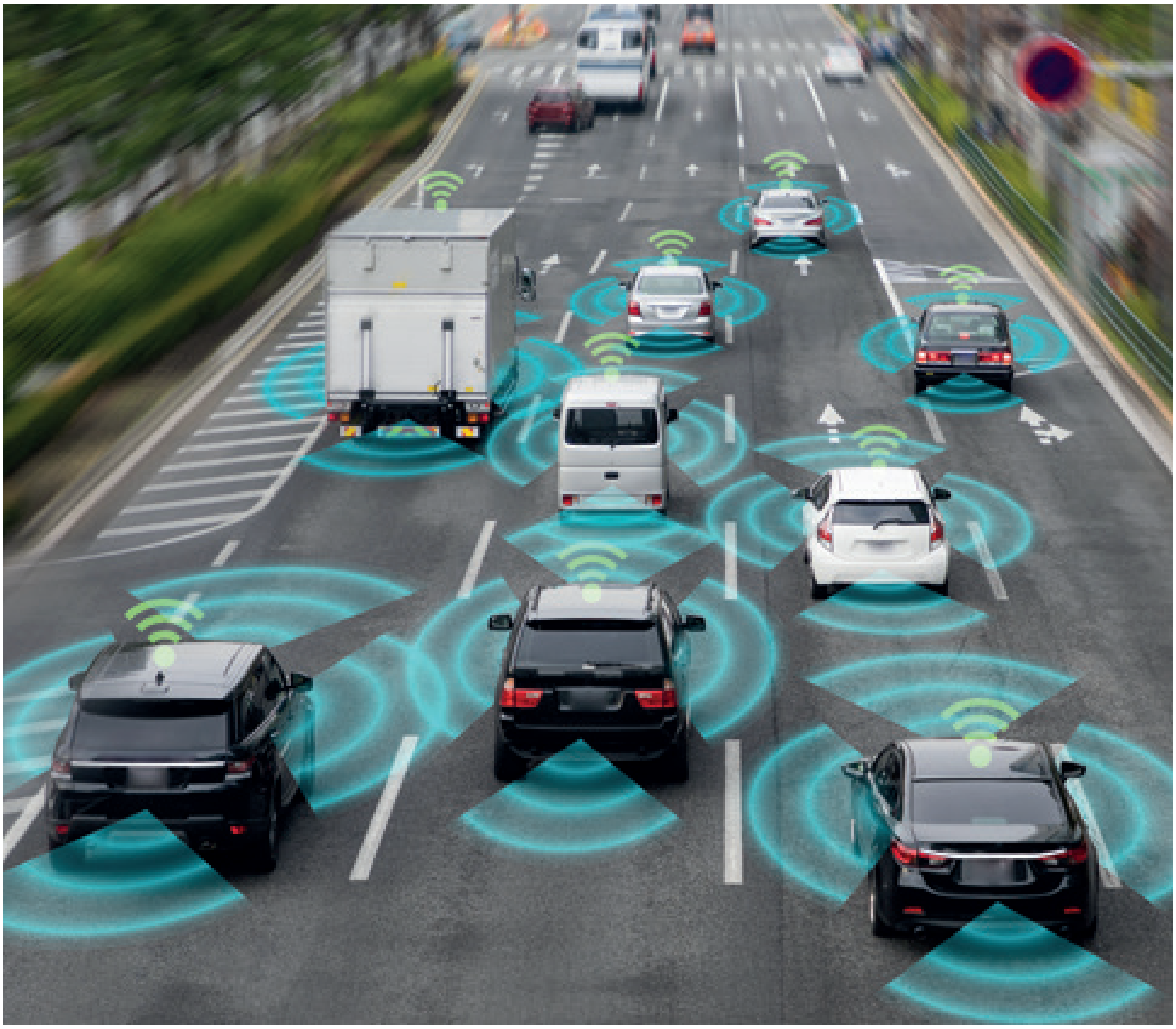
caused by autonomous vehicles (damage to property or to people), with decision makers having to decide who will be liable. Some initiatives are already being conducted, and Germany for example is considering requiring a black box that would record whether technology or a human driver was driving at all moments of the ride. Nevertheless, the driver and owner remain liable if the vehicle is operated in autonomous mode.

Regulators should work co-operatively with other stakeholders such as manufacturers, drivers and passengers to address these issues so that ethical decisions are made consciously.

There also is a great need for a policy framework that will regulate data access and exploitation as well as data security before a complete roll-out of autonomous vehicles.

Another concern that will arise is job losses. Technological developments will cause workforce and industry displacement. Governments will have to take steps to prepare for those losses. Policy makers could regulate the number of taxi licences they issue in order to manage the long-term reallocation of labour. At the same time, some kind of compensation for income losses from unemployment and job retraining could be provided.

Most business models centred around mobility as-a-service imply a higher utilisation rate of vehicles than nowadays. Moreover, large B2B charging providers can be expected to emerge. These two factors have far-reaching consequences both for EV sales and for the grid.



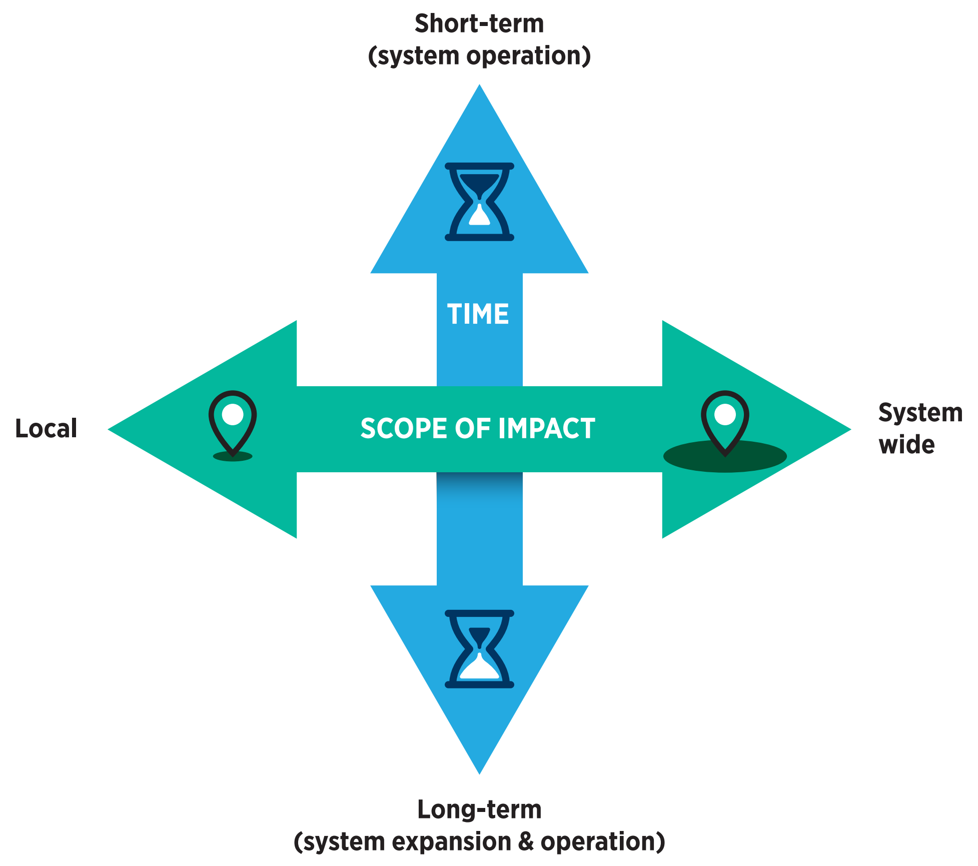
6. SMART CHARGING IMPACT ON THE GLOBAL ENERGY SYSTEM

As explained in the previous sections, smart charging will be key to maximising synergies between EVs and VRE generation. Different EV charging strategies may have somewhat different impacts based on the energy system's characteristics. The dominant source of VRE present in the system and changing mobility patterns also impact the strategies for EV grid integration.

The relevant angles for the analysis of these impacts are depicted in Figure 30:

- The first is the geographic scope of the analysis. The impacts of EVs on system operation are bigger in isolated systems with a high share of variable renewables that are more difficult to balance than in interconnected systems. Impacts of uncontrolled charging are higher in these systems due to limited or completely absent sources of flexibility from interconnectors. Assessing the added value of V1G and V2G smart charging in such extreme cases is important to understand the impact of different grid integration strategies. Local impacts of renewable energy sources and EV charging in distribution grids were also assessed in both the short and long terms.
- The second is the time frame of the analysis. Both the short-term impacts on operational planning in the system and the impacts of distinct EV charging strategies on the evolution of the system in the long-term need to be assessed.

Figure 30: Angles of the analysis



The analysis of the system-wide impact is based on modelling of isolated systems. The methodology used for the model, including assumptions and constraints, is discussed in Annex 5. The assessment of local impacts is based on external case studies. The exercise provided valuable insights and may inspire further investigations that were beyond the scope of this report. Those may include modelling of interconnected systems as well as isolated systems combining smart charging with secondary use of EV batteries as stationary batteries and the battery swapping systems. Further study also may focus on hybrid systems composed of renewables (solar PV and wind), battery storage and charging infrastructures that are approaching practical application on renewables-abundant isolated islands (*e.g.*, in northwest China) and for industrial parks.

6.1 System-wide impact

Two types of isolated systems are modelled for the system-wide impact assessment, as explained further below.

The following key performance indicators are used to assess the impact on these isolated systems, expressed in yearly values:

- **Renewable energy curtailment (%)**
- **Peak demand reduction/increase (%)** compared to business as usual
- **CO_2 emissions reduction (%)**
- **Average electricity cost (EUR/MWh)** calculated as the average short-run marginal cost of electricity generation.

The cost of the grid, communications and losses are not assessed in this simplified modelling.

Four scenarios enabling an assessment of the key EV innovations influencing renewable energy integration into power systems were defined. These are used to assess the impact of two innovations on the power system side and one on the mobility side, applied both separately (isolation of the effects) and together (synergies).

The first three scenarios assume no advances on the mobility side. The shift towards mobility as-a-service (MaaS) remains limited to current levels. Individual car ownership remains prevalent – that is, the number of cars is affected by economic development in each country. At the same time, the number of EVs rises as the total cost of ownership keeps falling. The opportunity costs of not driving (lost revenue from the transport service) are low:

1. **BAU (business-as-usual) scenario** assumes that current EV deployment trends will continue until 2030, whereas there will be limited innovations in the power sector. Therefore, the number of EVs will increase considerably, but their load and charging patterns remain uncontrolled.

2. **"Partial smart charging" scenario (named V1G)** assumes that EVs will be integrated in the grid through only unidirectional V1G smart charging.

3. **"Fully smart charging" scenario (named V2G)** assumes high innovation on the power system side and on the EV side in terms of technologies and business models. EVs are used as a source of flexibility for renewable-based power systems – that is, EV-grid integration is advanced including not only unidirectional smart charging (V1G) but also V2G, and second-life batteries become a competitive source of flexibility for the grid, used for peak shaving as well as for balancing of the grid close to real time.

However, the final scenario assumes important changes in mobility patterns:

4. **MaaS[ive] smart charging scenario** assumes full innovation on the power system side (as in the "fully smart charging" scenario) and complements it with high innovation on the mobility side. It reflects major developments towards mobility-as-a-service thanks to ICT developments (highly efficient car sharing, intermodality) and the evolution of EV technology towards fully autonomous driving that translate into a substantial drop in individual car ownership.

Table 16 summarises the scenarios.

Table 16: Definition of scenarios according to the level of innovations

Level of innovations in the scenarios		Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU	**"Partial smart charging" or V1G**	**''Fully smart charging" or V2G**	**MaaSive**
EVs		Yes	Yes	Yes	Yes
Innovation in power systems	**V1G**	No	Yes	Yes	Yes
	V2G	No	No	Yes	Yes
Innovation in mobility business models	**MaaS**	No	No	No	Yes

Short-term impact on system operation

The case presented illustrates an isolated location with high solar irradiation, with an average yearly load factor for solar PV of 31%. The installed capacity in this system under the BAU scenario in 2030 amounts to around 2 700 MW. Solar represents around 27% of the generation mix, with the remaining generation consisting of 60% combined-cycle gas turbine, 9% biomass and 2% wind and others. The peak demand is around 900 MW, and by 2030 the location will reach a 50% EV penetration rate in the fleet, representing 100 000 EVs with an average battery size of 80 kWh.

The results of the modelling[8] are summarised in Figure 31. They clearly demonstrate the benefits of smart charging compared to uncontrolled charging (the BAU scenario):

- The implementation of V1G and V2G gradually reduces curtailment to zero levels. V1G reduces curtailment because it shifts the EV load to better match the availability of solar power. This is even more apparent in the presence of EV batteries for V2G services that allow for full exploitation of the solar resources and that shift their consumption in time by storing the electricity in the EV batteries and re-injecting it into the grid at times of high demand.
- Consequently, 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 during the day, peak load is reduced in the V1G scenario compared to BAU because the vehicles are not charged during the peak load. In V2G peak load is even more reduced because the vehicle battery is sending electricity back to the grid during times of high demand.
- And finally, the average electricity cost may fall. The V2G scenario shows a high reduction in cost since the modelling assumes that EVs are used as free batteries. In addition to the short-run marginal cost, prices in ancillary services markets may decrease if the limited demand of this market segment is served by abundant flexible EVs or other flexible loads.

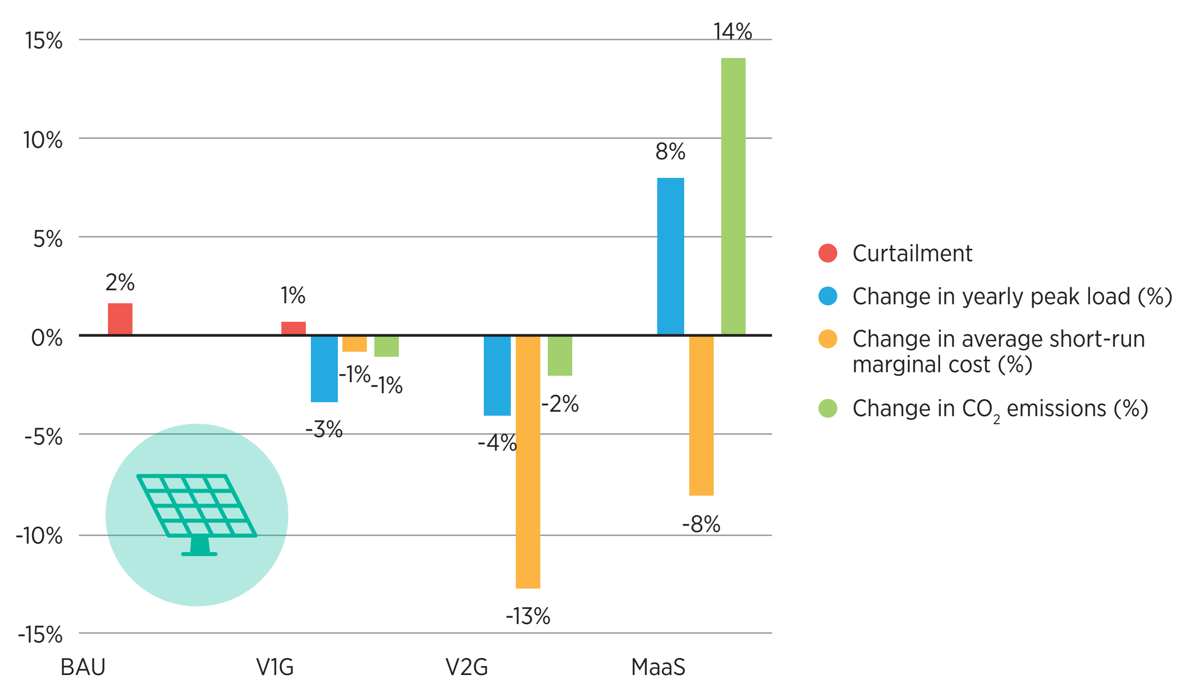
In addition, smartly charged EVs can be expected to have short response times, which is of crucial importance at shorter operational time frames.

However, once the advanced innovation on the power system side through smart charging is complemented with high innovation on the mobility side, some of the presented benefits may cancel out. In addition to V1G and V2G, the modelling of the MaaSive scenario assumes a major shift towards mobility-as-a-service that will occur hand in hand with widespread deployment of autonomous vehicles. This will translate into a substantial drop in individual ownership of cars. There will be fewer cars that will be driven much more than today's privately owned vehicles.

---

[8] The analyses were performed using the PLEXOS Integrated energy model software tool, copyrighted by Drayton Analytics Pty Ltd, Australia and Energy Exemplar Pty Ltd, Australia.

Figure 31: Short-term impact of EV charging on the selected key performance indicators



This will result in less overall EV battery capacity for the grid compared to scenarios without MaaS, lower availability of these batteries to provide grid services and even increased load during certain times because highly used vehicles will have less flexibility in charging. The details of how EVs were modelled in this case are provided in Annex 5. The modelling implicitly assumes that no other flexibility technology (such as stationary storage, demand response, etc.) emerges in the MaaSive scenario, to do what the no-longer-available vehicle batteries would have done.

Because of these developments:

- **Curtailment of solar may remain at zero levels.** Even if the sizes of available EV batteries have been reduced compared to the V2G scenario, the available battery capacity from V2G may still be large enough to store excess clean power and to shift its consumption in time, as in the modelled case.

- **But peak demand in the system increases** because of an increased yearly load that EVs bring to the system. Even though there will be fewer vehicles on the road, these will drive several times more than in the other scenarios, which in turn will increase the charging needs. Despite smart charging capabilities, the storage capacity of EV batteries is heavily constrained as vehicles spend most of their daytime driving and thus are not available for the provision of grid services.

- **Average electricity cost** could remain lower than in the BAU case. As solar was already fully exploited (zero curtailment in the V2G scenario), the cheapest way to fulfil the extra load is by increasing the load factor of gas-based generation, therefore dispatching combined-cycle gas turbines more than in BAU as baseload. The hourly short-run marginal cost is set by the most expensive units dispatched. The average system costs could be lower in the MaaSive scenario compared to BAU despite the higher system peak if in most hours, the dispatch favoured cheaper baseload units rather than the peaking units (which bring up the marginal cost). This is the case in the modelling exercise, where compared to BAU, gas peaking units run less and baseload units run more.

- **But increased dispatch of fossil fuel-based resources in turn leads to increased emission levels.**

Smart charging demonstrates significant benefits in the short-term operation of isolated systems in terms of curtailment mitigation, reduction of peak demand and electricity costs. However, the emerge of MaaS may cancel out smart charging benefits for peak demand reduction and CO_2 emissions reductions in the short term.

Long-term impact on system expansion

Long-term impacts of EV charging on the renewable-based power system can be illustrated using the same scenarios and key performance indicators as for assessment of the short-term impacts. However, two isolated systems were modelled this time: the same solar-based system as in the short-term case (2 700 MW) and a wind-based system with an average yearly wind load factor of 51% and installed capacity of 5 800 MW under BAU. This sub-section summarises the results for both modelled cases.

In the short-term analysis, the impact was assessed for different vehicle-grid integration strategies in system operation, along with how those would affect the key performance indicators from the first moment of implementation. On the other hand, short-term signals in the market have an impact on the long-term expansion of the system, and this is what is analysed in this sub-section: how different VGI strategies impact, in the long term, the system expansion and the operation of such future systems.

To account for this effect, the modelling software was changed to "freely" calculate the optimal capacity mix and to invest in new assets. It optimises the total system costs and meets the demand at the 2030 horizon and calculates the optimal dispatch by type of technology in hourly resolution. Different VGI strategies or the absence of VGI strategies (BAU scenario) would influence the system expansion, changing the optimal capacity mix. The model can optimally choose among four technologies – solar PV, wind, combined-cycle gas turbines and open-cycle gas turbines – to install extra generating capacity and meet the demand in 2030. Table 17 summarises the investment costs of these technologies.

Table 35 in Annex 5 shows the resulting capacity mix for the scenario after the expansion of the system for the specific solar and wind cases studied (the investment in new technologies is represented with the prefix "New").

EVs are expected to impact renewable energy investments, and particularly for isolated systems using wind and solar energy, as follows (Figure 33):

There is a high match between wind power production and EV charging profiles even with uncontrolled EV charging (BAU), and the implementation of smart charging will not significantly improve this match (the incremental change will be small). This is presented in Figure 32, which shows the EV charging profiles matched with the solar and wind availability. EVs mostly charge when wind blows. However, the exact match will depend on concrete wind production profiles that are more volatile than solar profiles. As an example, Figure 33 illustrates regional variation of load factors in a country with high wind potential.

- At the same time, wind investment may suffer from expansion constraints due to land availability issues in some locations. As that is the case in the modelled example, the wind case shows a similar capacity expansion across the scenarios. The model

Table 17: Investment cost of generation technologies used in the model

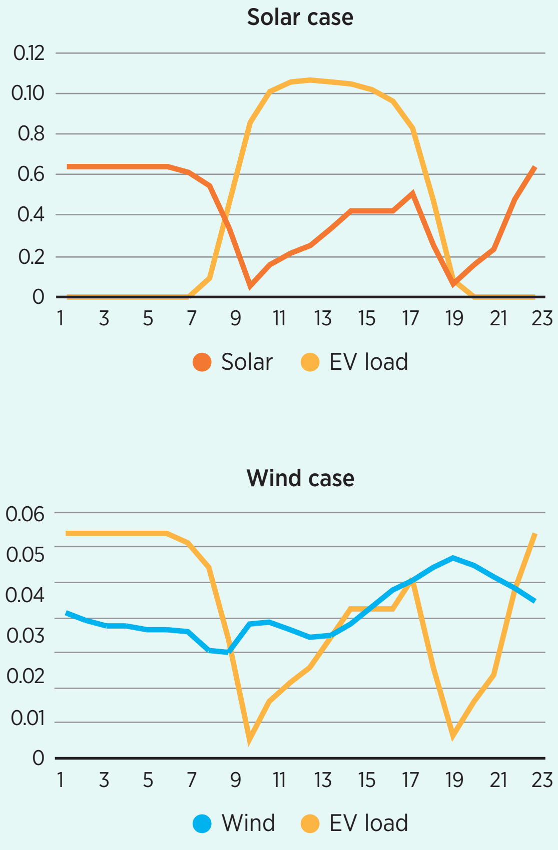
Technology	Investment cost in 2030 (USD 2016/kw)
New combined-cycle gas turbine	700
New open-cycle gas turbine	613
New solar	672
New wind	1 015

Figure 32: EV charging profiles matched with solar and wind availability

BAU

EV normalised daily charging profiles* in the wind and solar isolated cases when there is no innovation in V1G

Charging is concentrated at night and during working hours.



*All the values of the 24h sum to 1.

V1G

EV normalised daily charging profiles in the wind and solar isolated cases when V1G is integrated

Price signals sent to EV users will shift the EV demand for charging to off-peak periods and will match it with the availability of renewable energy sources.

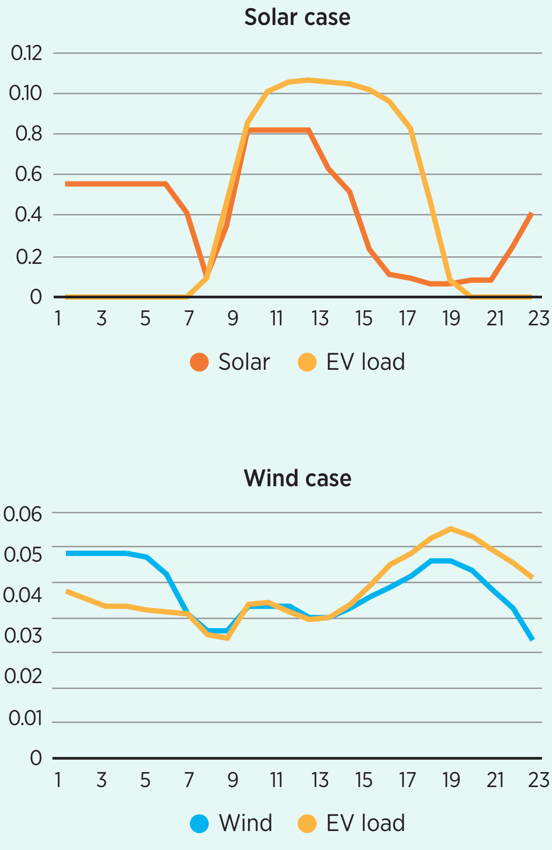
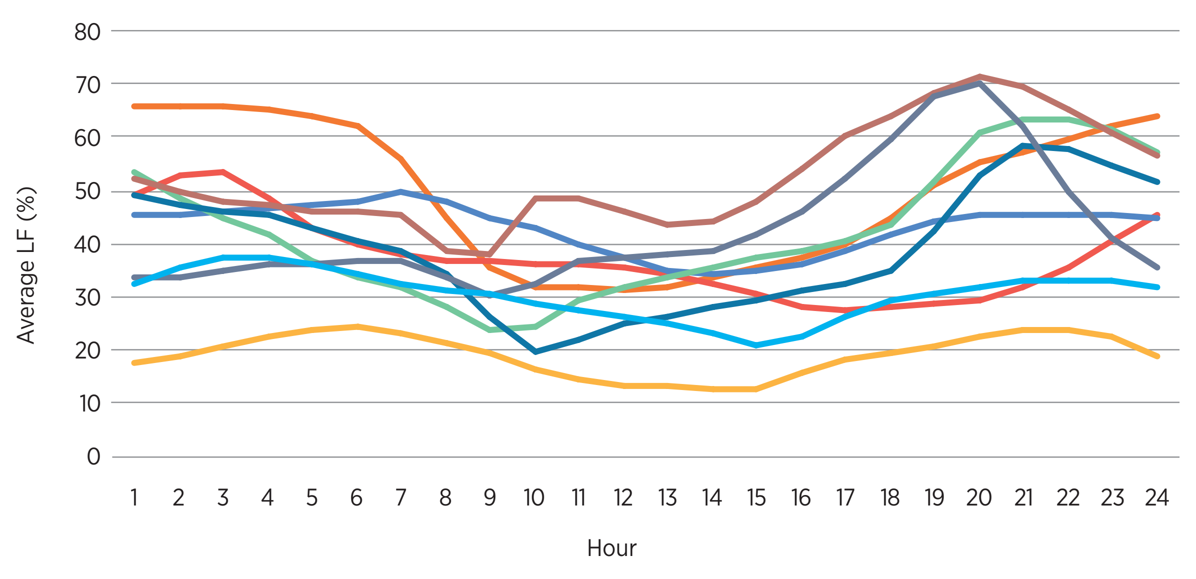


Figure 33: Regional wind production profiles in a country with high wind potential



Source: Tractebel, 2018.

chooses to invest in wind to its maximum limits already in the BAU scenario. The slightly different shares of renewables observed in the wind case are a consequence of different load factors of the technologies. This may not be valid for less isolated or interconnected systems.

- The solar generation profile varies according to the panel orientation (production from eastwards-oriented panels peaks in the morning and from the westwards-oriented panels peaks in the afternoon) and according to the weather (less irradiation with cloudy weather and in winter). Unlike wind, 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 even higher with solar, mainly in the V2G case with cheap batteries that can store excess renewable power not consumed instantaneously during the day and then dispatch it later.

Table 18 shows in detail the new capacity that the model requires in 2030 for the solar case in each of the scenarios. In the V2G scenario of the solar case, there is no wind investment because a massive solar investment is chosen over wind due to better load factor and cost-competitiveness as well as good match between solar profiles and smart charging patterns. The capacity expansion in the V2G scenario is also very significant as the modelling assumes that the EV batteries provide energy back to the grid for free.

- However, under the MaaSive scenario, the renewable share can be expected to cancel out and to return to reference values (BAU). This is a consequence of increasing the EV yearly load but not bringing enough storage capacity to the system to be able to economically integrate more renewable energy. In this case, the model finds it more cost attractive to invest in baseload combined-cycle gas turbines than to invest in large amounts of solar that would eventually have to be curtailed because batteries will not be able to integrate it.

Smart charging results in greater benefits for systems with high shares of solar PV than of wind, due to a more predictable solar generation profile. In systems with high wind shares, there already might be a high match between wind power production and EV charging profiles, even with uncontrolled EV charging.

Table 18: Capacity expansion (MW) in the solar case in 2030

	BAU	V1G	V2G	MAASIVE
New combined-cycle gas turbine	604	580	257	631
New open-cycle gas turbine	0	0	0	0
New solar	337	370	1 137	443
New wind	32	32	0	34

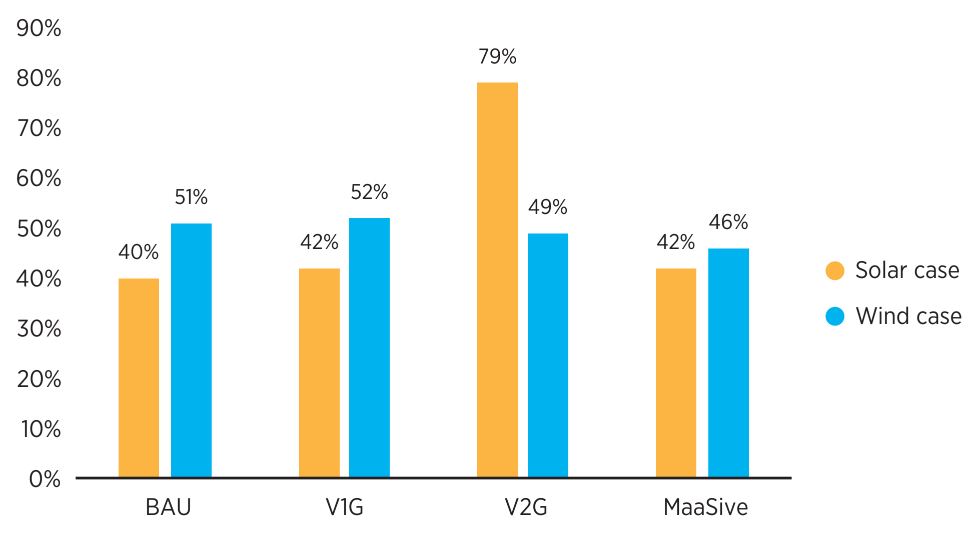
Note that the seasonality effect is low in the modelled region. In regions with higher seasonality, additional long-term storage may be needed, as EVs work as short-term storage and not to cover seasonal variations and to sustain the benefits of integrating renewables.

We can assume that the same innovations will be present until 2050. But their intensity will be influenced by other advances such as a digital revolution in the power and transport. Consequently, the renewable share is expected to be higher than in 2030 as more fossil fuel units will be decommissioned, and investments in renewables will be a more favourable option due to further reductions in the capital expenditures of both generating and enabling technologies. The increased share of smart charged EVs will also increase system flexibility to balance for daily variations in the system with an increased renewable share.

This could work in the same way for the case of wind, with the only difference that the generation profile of wind si less predicatble than the one of solar. However, in our "wind case" this does not apply as the maximum capacity of wind was already installed in BAU , and expension of wind capacity was not posibile due to limited land. The small differences between

Using EVs as batteries (V2G) could facilitate the integration of high share of solar generation in the grid by storing the excess solar generation during the day and inject it into the grid when demand peaks in the evening, for example. This would also keep the solar generation valuable and incentivise further deployment of solar PV instalaltions (as Table 18 illustrates).

*Figure 34: Renewable shares in generation in wind- and solar-based systems under different charging scenarios (long-term impact)**



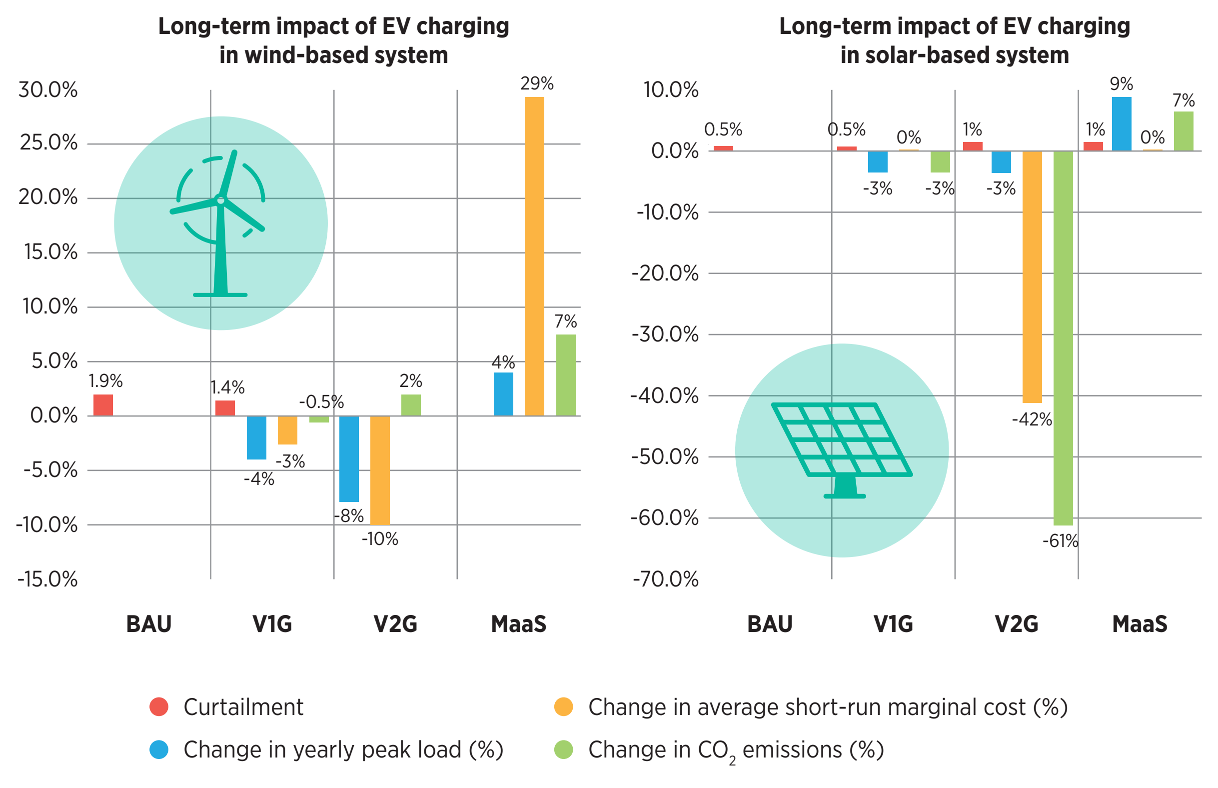
**Renewable shares include solar, wind, geothermal and biomass generation (with no hydropower in the system).*

wind generation in different scenarios is given by the differences in the level of curtailments.

The power mix evolution in turn affects the different key performance indicators, mostly in line with the trends observed in the short-term analysis and reinforcing the identified benefits, as described in Figure 35:

- **Yearly peak load** effects are similar in the short-term analysis – that is, smart charging scenarios lead to peak decrease, and the MaaSive scenario leads to a peak increase, with no major change for solar- and wind-based systems.
- **Decrease in CO$_2$ emissions** is driven by higher renewable shares in the system in both the solar and wind smart charging cases. Increased renewables also could mitigate the emissions increase in the solar MaaSive scenario, compared to the short-term impact. However, the magnitude of emission decrease in the solar V2G scenario is rather bullish in the model due to the simplified assumption that batteries will be free for the system, as explained above. In the wind case, emissions may rise significantly under a MaaSive scenario if barriers to further wind investment are not overcome.
- The **decrease in the short-run marginal cost** also largely follows the rising share of renewables. Unlike the actual drop in this cost compared to uncontrolled charging in the short-term MaaSive case, the price is similar to BAU in the long term.
- **High variations of curtailment** are observed when V1G or V2G are modelled (for solar curtailment in the solar case and for wind curtailment in the wind case). Overall, curtailment is slightly higher than in the short term but still under control. The model optimally chooses to increase the amount of renewable installed capacity in the system and chooses to curtail where this is more economically efficient than installing new capacity.

Figure 35: Long-term impact of EV charging



In the longer term, smart charging (V1G and V2G) would make it possible to spread demand to off-peak hours and to hours with high renewable generation, in turn allowing for increased dispatching of VRE (reducing VRE curtailment). It also will contribute to further yearly peak load reductions in both solar- and wind-based systems compared to business as usual .

EVs used as batteries (V2G) open the door to the integration of solar PV and, at the same time, greatly reduce the average system electricity cost – that is, facilitate cheap renewable-based systems. This will well compensate for slightly increased curtailment values.

With mobility-as-a-service – where EVs bring a much higher load to the system and provide less battery capacity for grid services – the benefits of V2G in terms of renewables capacity and peak load reduction largely cancel out.

Results from other similar studies

Impacts of uncontrolled EV charging versus smart charging on power systems have been assessed in external studies as well, many of which focused on power systems that already have high shares of VRE today (such as California or Germany). Table 20 provides an overview of results of several exemplary studies. In line with the case modelled for the purposes of this study, they 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). Research on the German power sector also showed that by utilising wind- and solar-oriented charging approaches, the share of renewable energy used for EV demand can be more than doubled (Kasten *et al.*, 2016).

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 – will still need to be carefully studied.

6.2 Local distribution grid impact

Short-term impact on operation of local distribution grid

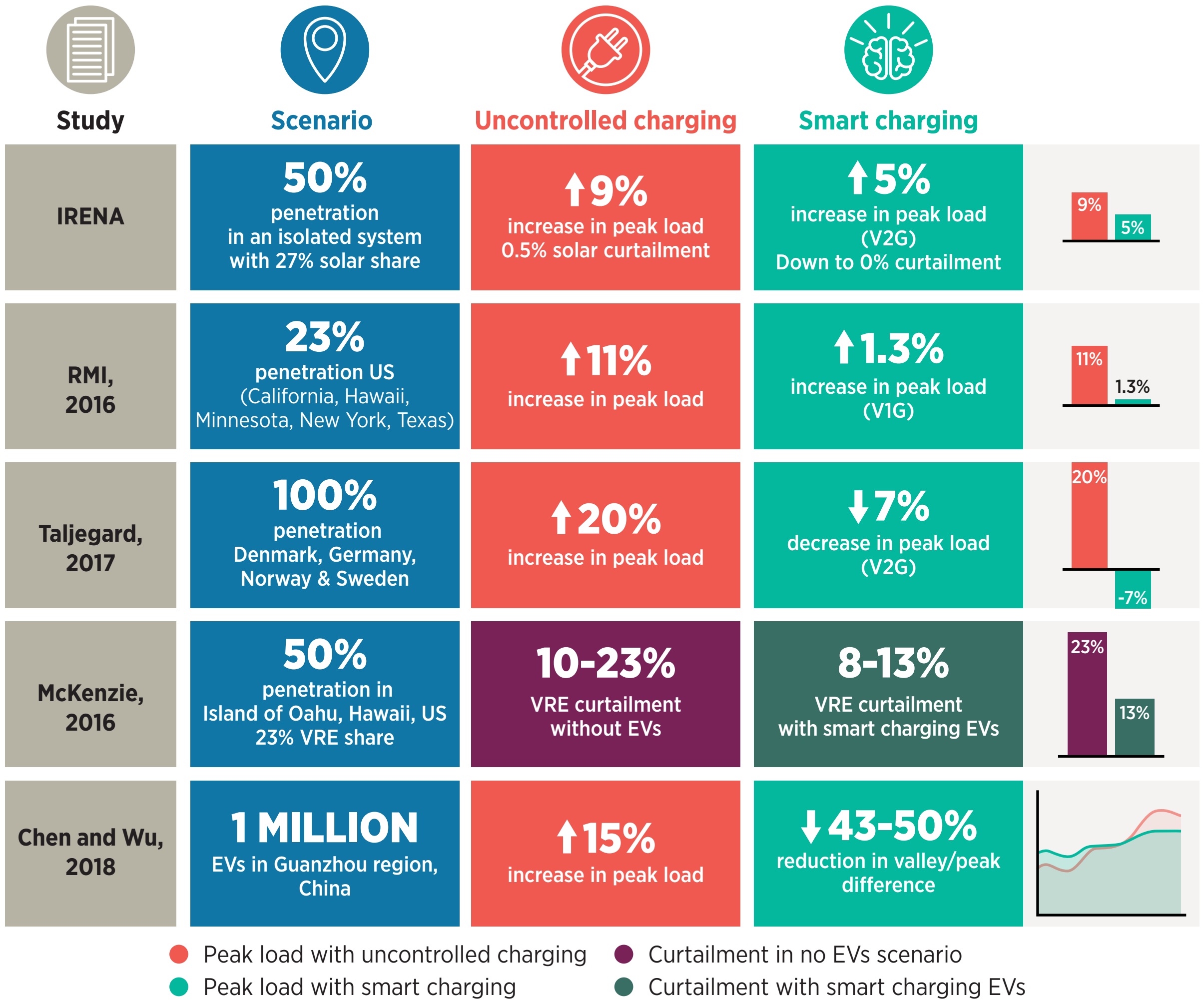
Even in interconnected systems, high penetration of VRE as well as uncontrolled penetration of EVs increases the variability of local residual demand. If there is high local penetration of variable renewables, local curtailment may be very high due to overvoltage and transformer overload. Local injection of active power from VRE increases voltage at the grid injection point. The hosting capacity of lines is limited by transformer loading capacity and critical line loading. If these limits are often exceeded, the "saturated" transformers and lines need to be reinforced. Moreover, if local supply exceeds local demand, the generated electricity would increase the voltage levels of the distribution grid.

Furthermore, EVs that are not charged in a smart way represent a significant challenge at the distribution level designed to facilitate unidirectional power flows, characterised by lower voltage levels and mostly radial grid structure.

With smart charging, feed-in of solar PV can be optimally used for EV charging. The PlanGridEV project co-financed by the EU is aimed at designing planning rules and operational principles for the optimal integration of EV in different local network designs. Simulations within this project demonstrated that (PlanGridEV, 2016a):

- With conventional charging, the transformer saturation increases as the number of EVs increases. However, with smart charging, the saturation of the transformers improves for the same number of EVs. This is because the EV demand peak does not coincide with the conventional demand peak. Smart charging can decrease reverse power flows from distributed generation to the transformer. The reduction of reverse load is represented by the purple curve in Figure 37.
- Voltage profiles can be positively influenced by smart charging, as illustrated in Figure 38. Smart charging mode makes it possible to reduce overvoltage and to keep the grid voltage sTable in a low-voltage distribution network. The voltage curve is smoothened. This effect can be realised mainly during the day via public charging or office charging.

Figure 36: Examples of studies assessing the impact of EV charging strategies



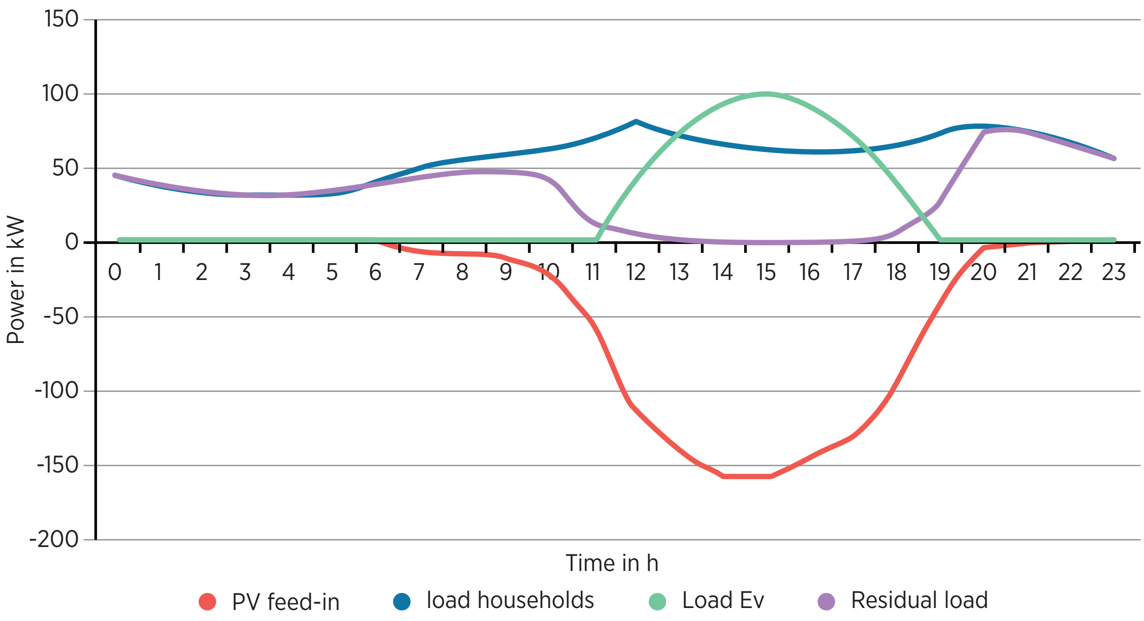
Study	Scenario	Uncontrolled charging	Smart charging
IRENA	**50%** penetration in an isolated system with 27% solar share	**↑9%** increase in peak load 0.5% solar curtailment	**↑5%** increase in peak load (V2G) Down to 0% curtailment
RMI, 2016	**23%** penetration US (California, Hawaii, Minnesota, New 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

A simulation of a location with three distribution feeders (Tractebel, 2018) demonstrated that only unidirectional smart charging (V1G) can reduce solar PV curtailment by 20% per year. If combined with a stationary battery, curtailment can be reduced by 83% per year compared to a scenario with uncontrolled charging.

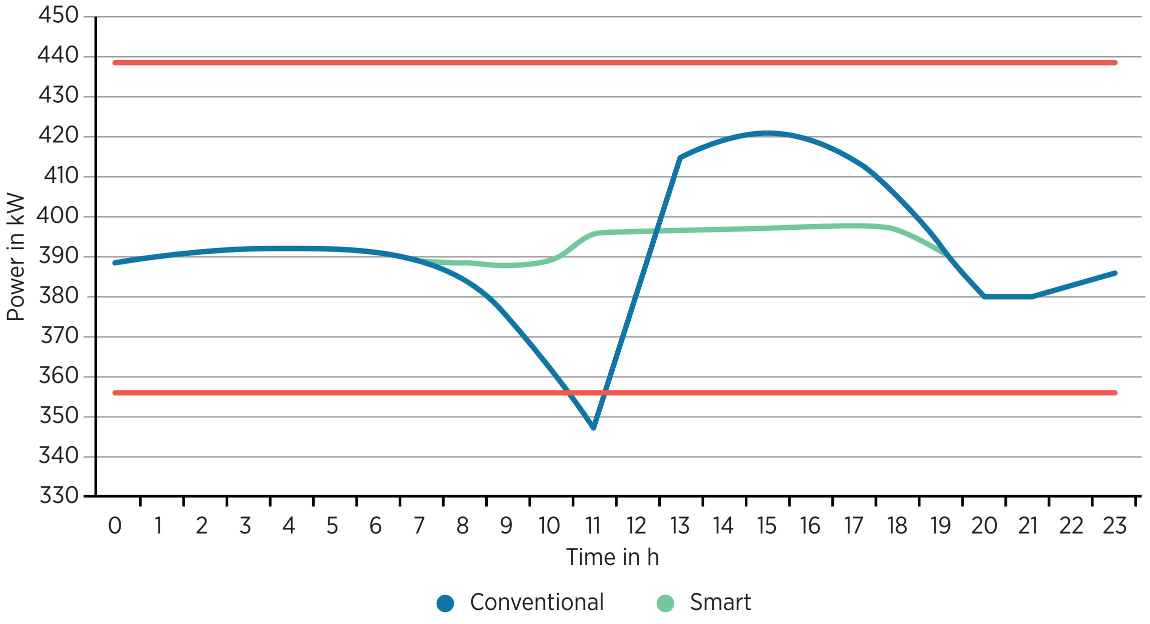
While the system-wide effects of smart charging will be more significant in isolated systems than in interconnected systems, local congestion mitigation benefits can be tapped in both types of systems. Smart charging can reduce reverse power flows and transformer overload, increasing the hosting capacity of distribution grids. It also helps mitigate overvoltage in low-voltage grids with high shares of VRE.

Figure 37:Power profile with smart charging



Source: PlanGridEV, 2016b.

Figure 38:Voltage profile for smart and conventional charging at noon



Source: PlanGridEV, 2016b.

Long-term impact on distribution grid expansion

Mass adoption of EVs has an impact on electricity infrastructure. Bottlenecks or grid congestions may occur when the existing transmission and/or distribution lines, or transformers, are unable to accommodate all required load during periods of high demand – such as simultaneous charging of thousands of EVs – or during emergency load conditions, such as when an adjacent line is taken out of service.

The impacts of EV charging on congestion in the distribution grid can be illustrated in two separate case studies from two medium-sized European distribution grid: Stromnetz Hamburg (Germany) and Endesa (Spain).

i. EV charging impact on Hamburg's distribution grid

Hamburg is currently the city with the highest number of charging points in Germany (several hundred charging points in households and 810 public charging points as of November 2018). The city expected to install 1 000 public charging points by the beginning of 2019. Electrification of public buses and EV growth are the most critical drivers of load development in the city. The majority of EVs will be in the suburbs where, in Hamburg's case, the grid is weaker (Pfarrherr, 2018).

The local distribution system operator, Stromnetz Hamburg, ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point loads of 11 kW and 22 kW. Stromnetz Hamburg assessed two scenarios:

- *Scenario 1:* A 3% EV share, corresponding to 20 000 EVs loading in private infrastructure, will cause 200 bottlenecks. This would cause issues in the low-voltage grid.

- *Scenario 2:* A 9% EV share, corresponding to 60 000 EVs loading in private infrastructure, will cause bottlenecks in 800 out of 6 000 feeders, or 15% of the feeders in the city's distribution network (Pfarrherr, 2018).

To avoid these critical situations, Stromnetz Hamburg assessed the investment needs for reinforcing the local grids. Scenario 2 would require reinforcing approximately 10 000 km of 0.4 kilovolt (kV) cable lines resulting in an investment of at least EUR 20 million (around EUR 200/metre of cable). This investment estimate does not include the replacement of overloaded transformers, which would be significant as well.

In addition to the costs for reinforcing the local grids, one more challenge, perhaps more complex than the monetary implications, would be finding the workforce capacity to reinforce the grid and to obtain the permits, as well as the public acceptance of works that require closing many roads in the city to replace underground cables for periods of several months or even years.

Given the magnitude of the challenge and the costs needed to reinforce the local grids, Stromnetz Hamburg is exploring an alternative solution to address the problem. The key is to decrease the simultaneity, meaning decreasing the number of EVs that are charged at the same time on the same local grid. For that, a smart solution using digital technologies is being tested, which includes:

- Every household with a charging point has to report it to the distribution system operator. This information has not been required yet.

- Measure the loads on the 0.4 kV cables, which at the moment is not required in the city of Hamburg. This will make it possible to identify the bottleneck problem as soon as it emerges.

- A real-time communication system that enables the distribution system operator to reduce the load of the charging points needed to address the problem. The 11 kW charging points, for example, can reduce their load from 16 amperes (A) to 8 A, allowing EVs to be charged but in a longer period of time.

For this project, Stromnetz Hamburg partnered with Siemens, which will install 30 control units and monitor the private charging infrastructure loads. This will help them anticipate congestion issues and plan the network based on the load profiles. The estimated cost of this solution is around EUR 2 million, which is just 10% of the cost of reinforcing the cables (without including transformer costs) in a conventional solution. They also plan to start a close collaboration with the charging point operators to build a strong IT and communications infrastructure to link the charging point operators and the grid.

Even where the technical solution is feasible, full implementation of it would require the engagement of consumers as well as the more than 400 electricity retailers in the City of Hamburg to use, for example, a time-of-use price incentive to allow the distribution system operator to control its charging points based on the local grid needs. The case of Hamburg shows not only the impact that EVs may have on local grids, but the potential solutions to address it that may require a combination of digital technologies, new business models and market regulation to engage all the needed actors.

ii. EV charging impact on the Spanish distribution grid

The case assessed the potential cost of distribution grid reinforcement at different levels of EV penetration in the transport sector and at different levels of concentration of charging points in low-voltage networks, under two scenarios. The higher the concentration of charging points – for example in a large parking lot – the higher the probability that local overloads could occur once many vehicles start charging at the same time.

The two scenarios included:

- The first scenario without smart charging. The only way to avoid local congestion in this scenario is to substantially reinforce the overloaded section of the network (*i.e.*, the "copperplate" solution).
- The second scenario with installation of smart charging – that is, a charging system allowing a certain level of control including variation of charging current. It is V1G assuming basic allocation of charging capacity in one transformer: when too many cars are trying to charge at the same time, the system rotates them to allocate capacity. This system makes it possible to charge all the EVs by distributing the available power across all the vehicles and charging them in sequence, without overloading the local feeder. Network reinforcement is assumed when power is insufficient to charge all the vehicles (*e.g.*, overnight).

The results of the case study, based on real data from slow charging (4 kW) part of the distribution grid and extrapolated to the rest of it, are summarised in Table 19. They demonstrate the scale of savings in terms of distribution network cost avoidance: at 15% of EV penetration, smart charging allows for substantial savings of more than EUR 1 billion compared to business as usual (Endesa, 2014).

Table 19: Distribution grid reinforcement under "not smart" versus "smart" charging scenarios

		Distribution grid reinforcement cost WITHOUT smart charging (million EUR)		Distribution grid reinforcement cost WITH smart charging (million EUR)	
		Level of EV penetration in the local distribution grid		Level of EV penetration in the local distribution grid	
		5%	15%	5%	15%
Concentration of EV charging points in low-voltage networks	20%	**550**	**1 502**	**213**	**607**
	30%	**603**	**1 661**	**229**	**654**
	40%	**641**	**1 774**	**235**	**672**
	50%	**672**	**1 867**	**236**	**675**

Source: Endesa, 2014.

7. CONCLUSION – POLICY CHECKLIST

As the outlook analysis demonstrates, the EV potential for VRE integration between today and 2030/2050 is expected to increase substantially due to expected acceleration of electrification of the transport sector, technology innovation allowing for increased battery sizes and continuous uptake of smart charging capabilities for V1G, V2G and V2X on the side of both the vehicles and the charging infrastructure. Digitalisation can both facilitate customers' acceptance and engagement and drive new business opportunities.

At the same time, several barriers may slow the ability of this growing potential to materialise. Today one of the main barriers to EV uptake is the lack of charging infrastructure. As no clear business model exists yet for the development of such infrastructure, public support (regulatory incentives, policy targets, etc.) is needed in most cases. With the uptake of EVs, VGI strategies should be enforced, to *not only minimise the impact of such extra load on the power system, but also harness the synergies* between EVs and renewables in the system, which creates the need for increased flexibility. Turning the potential of V2G and V2X demonstrated in pilots to materialise in practice is a complex task even if both hardware and software are in place. Smart charging following renewable energy generation patterns needs to be incentivised by appropriate market design and automated control.

Policy support and regulation will be needed to overcome these challenges. Governments have a toolkit of policy levers that can be grouped into the following categories: monetary and non-monetary incentives, regulatory measures, advocacy and public relations, and public procurements. Local authorities should also take the lead in developing and testing them. And they will need to facilitate interaction between the mobility providers and the energy utilities operating the grids and supplying electricity, rather than building silos between them.

This results in 3 major recommendations and 13 concrete action points for policy makers, summarised in Figure 42:

Decarbonisation of the power system and decarbonisation of mobility must continue hand in hand, not one without the other, as that would decrease the potential gains from both.

On the one hand, a decarbonised power system with a high share of renewable power generation ensures lower well-to-wheel emissions of EVs, and therefore the decarbonisation of the transport sector. On the other hand, smartly charged EVs will improve the integration of high shares of renewables in the power system, by harnessing synergies between them at both the system and local levels. To make this source of flexibility available at scale, EV costs will need to decrease further, becoming competitive with ICE vehicle costs. Charging infrastructure needs to be developed further to overcome range anxiety and to facilitate mass adoption.

Action point 1: Design ambitious transport targets

Besides keeping high ambitions in renewables (or putting them in place where they are still missing), the ambition in e-mobility at the national level should rise. Countries should learn from first movers that have already implemented mobility targets and support. They should focus not only on passenger vehicles but also on other forms of road transport such as public transport. Leading by example, cities and regional public authorities should revise procedures and could even set targets for public procurement for buses and vocational vehicles to incentivise the creation of a premium market.

Road transport targets should be separate from other mobility sectors such as aviation or navy to be effective.

In addition to mobility targets and CO_2 standards that are already in place in some countries, CO_2 reduction targets for transport would be of relevance.

Action 2: Support charging infrastructure

Governments and local authorities in nascent EV markets should design charging infrastructure incentives to kickstart these markets, following already established good practices. All governments should address complex market segments such as ultra-fast charging and multi-unit dwellings. Permitting procedures for charging infrastructure installation should be streamlined.

Action 3: Keep or introduce temporary incentives for EVs

EVs are expected to become cost competitive with ICE vehicles in most locations and for most types between 2025 and 2030. But while sales of EVs are expected to increase rapidly in the main automotive markets, the global growth is far from uniformly distributed. Direct monetary incentives for EVs thus should be introduced and eventually phased out following local circumstances and needs.

Eventually, non-monetary incentives should become more prevalent. For example, local governments should also be inspired by the best indirect incentives such as emission-free zones.

Action 4: Deploy more renewables

Countries and international organisations should put in place ambitious renewable energy targets where this is not yet the case. Where such policies already exist, they should be updated regularly and maintain a high level of ambition (IRENA, 2015).

> ***Smart charging will be crucial to tap the benefits of EVs for the power system and vice versa. Smart charging facilities need to be a focus of attention as EV sales soar between now and 2030.***

In some regions, wind production profiles may at times 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. Therefore, the incremental benefits of smart charging will be particularly significant in solar-based systems. By shifting charging to better solar PV generation and implementing V2G, increased shares of solar could be integrated at the system level and the local grid level, mitigating the need for distribution grid investments. At the same time, the benefits of smart charging with solar may not be easy to achieve without incentives, as most home charging takes place at night, and fast charging that will be increasingly developed has generally low potential for VGI.

Action point 5: Standardise and ensure interoperability between EVs and EVSE

Keep pace of the standardisation process at the international level (IEC) so that when EVs reach the mass market in the mid-2020s these standards can already be applied to facilitate smart charging at scale. They should be designed to respect data privacy and security.

Standardisation alone will not lead to interoperable solutions for recharging EVs. Interoperability is important to avoid multiplication of standards and to ensure compatibility and efficient communication. Common standards and interoperability between EVs, charging infrastructure and the grid are a precondition for smart charging to materialise. Interoperability of data exchange is also key for “roaming” customers – that is, customers who want to charge their vehicle outside the area of their home operator.

Action point 6: Start implementing smart charging in isolated systems and regions with high shares of renewable energy

Focus first on isolated systems such as islands where EVs will have less competition with other types of flexibility (due to absence of interconnection, etc.). In turn, early implementation of smart charging can have a positive impact on power system expansion, especially in solar-based systems.

Areas with high local penetration of distributed generation (mainly from solar PV) that have high local potential for synergies with smartly charged EVs should be further exploited in priority.

This should be complemented with greater commercialisation and demonstration of smart charging solutions, which will enable a real-world validation of research, development and innovation done in the field.

Action point 7: Design smart charging strategies while keeping in mind the power mix

Regulation focusing on long-term investments should allow network solutions beyond the traditional fit-and-forget approach. Smart charging should be developed while keeping in mind the specificities of individual power systems.

In solar-based systems, focus on workplace charging and other types of commercial charging. For EV charging to complement solar, such 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. Employers may offer their employees free charging with renewable electricity at the office (and they may use it later at home). For that, pre-cabling and smart chargers should be promoted at commercial buildings.

In those wind-based regions/systems where wind blows more in the evening and at night, focus mainly on home charging to take place at night and adjust it dynamically to variations in wind production.

Action point 8: Locate charging optimally from both a mobility and a power system perspective

Support most optimal solutions for mobility needs and grid needs as of the planning stage: developers need to be able to access distribution grid data about local grid congestion to be able to locate charging systems at more optimal grid locations.

Smart charging will need to be further complemented by including energy storage and local renewable energy sources (mainly solar PV) for fast-charging sites to reduce the costs and need for capacity upgrades of fast-charging stations.

Action point 9: Develop the electricity market design for smart charging, and adjust regulation

Developing V2G and other EV battery business models will need to be supported by more than one revenue stream (revenue "stacking" of batteries). Tariffs will have to be adjusted to avoid double charging of batteries for network use, taxes and levies. Market incentives will need to be put in place that will provide appropriate signals to drivers as well as market players such as aggregators, namely:

- Inform customers and empower them by encouraging appropriate price signals in all geographies. Dynamic pricing and update of distribution grid tariffs will be necessary to signal to the cars the best moments to charge and discharge. At the same time, increased automation will enable both drivers and service providers to manage this system.

- This will be best put in place by designing wholesale markets that enable access of aggregated resources and retail markets, allowing for price volatility.

- Additional mechanisms for local procurement of flexibility by distribution system operators will need to be designed, together with flexibility platforms co-ordinating sources between system-wide and local use.

Action point 10: Use alternatives to complement grid charging

Redundant battery storage at the stations or battery swapping with supplementary battery storage that can draw power from the grid at the most optimal time and then use it to charge EV batteries could complement grid charging.

Do not underestimate the long-term evolution of the mobility sector, as doing so could have a tremendous impact on EV availability for smart charging.

EVs will remain primarily means for transport and will serve only secondarily as "batteries for the system". Mobility-as-a-service (MaaS) and the eventual shift towards fully autonomous vehicles, mainly in urban areas, will not only drive the development of new technologies like wireless charging, it will also move charging from home/office to hubs.

Action point 11: Support holistic battery and charging research and development (R&D)

Battery and charging R&D should be supported to consider the mobility and the grid needs at the same time. In this way batteries that are already suiTable for grid needs will maintain these capabilities.

Action point 12: Study implications of MaaS for EV flexibility

A wider e-mobility uptake will contribute to more system flexibility. The implications for 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 – should be carefully studied. Urban areas in developed cities may be particularly impacted, and rural areas less.

Action point 13: Build charging hubs in the most optimal locations considering infrastructure needs

Planning of charging (e-hubs) should be closely co-ordinated with mobility plans to optimise between the grid and the mobility needs, to avoid expensive grid reinforcement and to maximise renewable energy consumption.

Figure 39: 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

REFERENCES

ACEA, 2017. Registration figures. European Automobile Manufacturers Association, Brussels. *www.acea.be/statistics/article/Registration-Figures*.

AER, 2018. *The e-mobility revolution: impact of electric vehicles on the GB power system and emerging utility business models.* Aurora Energy Research, Oxford, UK.

AirQualityNews.com, 2017. "Ford and Deutsche Post DHL unveil electric van". *www.airqualitynews.com/2017/08/16ford-deutsche-post-dhl-unveil-electric-van*.

Ayre, J., 2017. "Mitsubishi announces V2G pilot project utilizing Outlander PHEVs in Amsterdam". CleanTechnica. *https://cleantechnica.com/2017/10/31/mitsubishi-announces-v2g-pilot-project-utilizing-outlander-phevs-amsterdam/* (accessed December 2017).

Bach Andersen, P. *et al.*, 2019. Parker Project Final Report. Energy Technology Development and Demonstration Program (EUDP).

Battery University, 2018. "BU-1003: Electric vehicle (EV)". *http://batteryuniversity.com/learn/article/electric_vehicle_ev*.

Bhunia, P., 2018. "China issues nationwide guidelines for road-testing of autonomous vehicles". OpenGov Asia. *www.opengovasia.com/china-issues-nationwide-guidelines-for-road-testing-of-autonomous-vehicles/* (accessed November 2018).

BMW and PG&E, 2017. BMW i ChargeForward: PG&E's Electric Vehicle Smart Charging Pilot. Pacific Gas and Electric, San Francisco. *https://efiling.energy.ca.gov/GetDocument.aspx?tn=221489*.

BNEF and McKinsey, 2016. *An integrated perspective on the future of mobility.* Bloomberg New Energy Finance and McKinsey & Company.

BNEF, 2018a. *Electric buses in cities, global edition.* Bloomberg New Energy Finance, London.

BNEF, 2018b. *Autonomous vehicles: Automakers' launch strategies.* Bloomberg New Energy Finance, London.

BNEF, 2017a. Electric vehicle data hub, global edition. Bloomberg New Energy Finance, London.

BNEF, 2017b. Global EV and charging policy support database, global edition. Bloomberg New Energy Finance, London.

BNEF, 2017c. *Long term electric vehicle outlook, global edition.* Bloomberg New Energy Finance, London.

BNEF, 2017d. "Microsoft uses AI to grow its smart grid, EV charging business". Bloomberg New Energy Finance. *https://about.bnef.com/blog/microsoft-uses-ai-grow-smart-grid-ev-charging-business/* (accessed November 2018).

BNEF, 2017e. "U.S. utilities offer multiple electric car charging rates". Bloomberg New Energy Finance. *https://about.bnef.com/blog/u-s-utilities-offer-multiple-electric-car-charging-rates/* (accessed July 2018).

BoA/ML, 2018a. From pump to plug: EV charging in cities – Major opportunity; major challenge. Bank of America Merrill Lynch.

BoA/ML, 2018b. From pump to plug: EV charging expert call series – What we learned. Bank of America Merrill Lynch.

Briones, A. *et al.*, 2012. *Vehicle-to-grid (V2G) power flow regulations and building codes review by the AVTA.* Idaho National Laboratory, Idaho Falls, Idaho.

BusinessWire, 2016. "Technavio announces top five vendors in the electric vehicle charging station market in China from 2016 to 2020". BusinessWire. *www.businesswire.com/news/home/20160614005085/en/Technavio-Announces-Top-Vendors-Electric-Vehicle-Charging*.

Camus, C., Farias, T., 2012. "The electric vehicles as a mean to reduce CO_2 emissions and energy cost in isolated regions. The São Miguel (Azores) case study". *Energy Policy*, Vol. 43: 153-165.

Catapult, 2016. *Mobility as a service: Exploring the opportunity for mobility as a service in the UK.* Catapult Tranport Systems. Conference in Birmingham, UK.

CEM-EVI, 2017. EV30@30 Campaign. Clean Energy Ministerial – Electric Vehicles Initiative.

CHAdeMO Association, 2018. "Members". www.chademo.com/membership/members (accessed November 2018).

CharIN, 2018a. "Members of CharIN e.V.". www.charinev.org/membership/members-of-charin-ev/ (accessed November 2018).

CharIN, 2018b. *The path to a global charging standard.* CharIN e.V.

Chase, A., 2016. *Economics of vehicle to grid.* E4Tech. www.e4tech.com/wp-content/uploads/2016/09/EV-grid-economics_E4tech_WEB.pdf.

Chen, L., Wu, Z., 2018. "Study on effects of EV charging to global load characteristics via charging aggregators". *Energy Procedia*, Vol. 145: 175-180.

Creara, 2017. *The electric vehicle – A major contributor to EU energy & climate policy objectives*. Creara, Madrid.

Daimler, 2016. "CASE: New strategic focus for Mercedes-Benz Cars strategy". www.daimler.com/innovation/specials/electric-mobility/case.html (accessed 27 December 2017).

de Brey, B., 2017. "Smart solar charging: Bi-directional AC charging (V2G) in the Netherlands". *Journal of Energy and Power Engineering*, Vol. 11: 483-490.

De Vroey, L., 2016. "Is vehicle-to-home or vehicle-to-grid suiTable for the electric vehicle user? Discussion from a one year intensive experience". Presentation. EVS29 Symposium, Montréal.

Deloitte, 2017. *Powering the future of mobility: How the electric power sector can prepare for its critical role in the new transportation ecosystem.* Deloitte Center for Energy Solutions.

Delta-ee, 2018. *The intersection between EVs and electricity – opportunities and threats*. Delta Energy & Environment, Edinburgh.

Demographia, 2017. "Demographia world urban areas". www.demographia.com.

Deutsche Bank, 2016. *Welcome to the Lithium-ion age.* Deutsche Bank Markets Research.

Dodgson, L., 2016. "Buses and batteries: A rising sector". Power Technology. www.power-technology.com/features/featurebuses-and-batteries-a-rising-sector-4904956/.

Dyble, J., 2018. "Understanding SAE automated driving – Levels 0 to 5 explained". Gigabit. www.gigabitmagazine.com/ai/understanding-sae-automated-driving-levels-0-5-explained (accessed July 2018).

EA Technology, 2016. "My Electric Avenue". http://myelectricavenue.info/.

EAFO, 2017. European Alternative Fuels Observatory. www.eafo.eu [accessed January 2018].

EC, 2017. EU Directive 2014/94/EU. *National plans for alternative fuel infrastructure*. Member States fiches. European Commission, Brussels.

ELinGo, 2018. *Technology for dynamic on-road power transfer to electric vehicles. Electric infrastructure for goods transport.* www.sintef.no/globalassets/project/elingo/18-0733---rapport-3---technology-for-dynamic-on-road----6-til-nett.pdf.

Endesa, 2014. *Smart Grids, Direccion de regulacion de E&P.* Endesa, Madrid.

Enel, 2017. "Enel acquires eMotorWerks to provide grid balancing solutions and tap into us e-mobility market". Enel. www.enel.com/media/press/d/2017/10/enel-acquires-emotorwerks-to-provide-grid-balancing-solutions-and-tap-into-us-e-mobility-market (accessed March 2018).

Enel, 2016. "Nissan, Enel and Nuvve operate world's first fully commercial vehicle-to-grid hub in Denmark". www.enel.com/media/press/d/2016/08/nissan-enel-and-nuvve-operate-worlds-first-fully-commercial-vehicle-to-grid-hub-in-denmark (accessed March 2018).

Enerdata, 2016. "Global energy research". Enerdata. www.enerdata.net/research/global-energy-research.html.

Energy Exemplar, n.d. *PLEXOS Guide.*

Engerati, 2018. "TenneT tests the blockchain to unlock flexibility". Engerati. www.engerati.com/energy-retail/article/blockchain/tennet-tests-blockchain-unlock-flexibility.

Engerati, 2017. "Can you recycle or re-use EV batteries?" Engerati.www.engerati.com/energy-management/article/energy-storage/can-you-recycle-or-re-use-ev-batteries (accessed January 2018).

EPRI, 2018. *U.S. National electrification assessment.* Electric Power Research Institute, Palo Alto. http://mydocs.epri.com/docs/PublicMeetingMaterials/ee/000000003002013582.pdf.

Eurelectric, 2015. *Smart charging: steering the charge, driving the change.* Eurelectric, Brussels.

Fagan, A., 2017. "Israel tests wireless charging roads for electric vehicles". *Scientific American*. www.scientificamerican.com/article/israel-tests-wireless-charging-roads-for-electric-vehicles/.

FEV, 2017. www.fev.com [accessed January 2018].

FleetEurope, 2017. "La Poste runs largest electric fleet in Europe". www.fleeteurope.com/en/news/la-poste-runs-largest-electric-fleet-europe.

Gallagher, C., 2018. "New government grant for electric car owners available". *The Irish Times*. www.irish-times.com/news/environment/new-government-grant-for-electric-car-owners-available-1.3342126 (accessed January 2018).

Ghatikar, G., Parchure, N., Pillai. R.J., 2017. "Integration of multifarious electric vehicle charging infrastructure flexibility. Applications for India". 1st E-mobility Power System Integration Symposium, Berlin. http://mobilityintegrationsymposium.org/wp-content/uploads/sites/7/2017/11/2B_4_EMob17_222_paper_Ghatikar_Rish.pdf.

Ghoshal, D., 2017. "Coming soon to India: Electric buses that can swap batteries at petrol pump-like facilities". Quartz India. https://qz.com/1033014/ashok-leyland-wants-to-bring-electric-buses-that-can-swap-batteries-at-petrol-pump-like-facilities-to-india/.

Gogoro, 2018. "Gogoro 1 Series – Easier". www.gogoro.com/smartscooter/1-series/plus/easier/ (accessed November 2018).

Goodwin, A., 2017. "Qualcomm's inductive charging road could pave the way to new EVs". CNET. www.cnet.com/roadshow/news/qualcomms-inductive-charging-road-could-change-the-way-we-build-evs/.

Guardian, 2017. "China to ban production of petrol and diesel cars 'in the near future'". *The Guardian*. www.theguardian.com/world/2017/sep/11/china-to-ban-production-of-petrol-and-diesel-cars-in-the-near-future.

Guinn, S., 2017. "EVSE rebates and tax credits, by state". ClipperCreek. www.clippercreek.com/evse-rebates-and-tax-credits-by-state/ (accessed December 2017).

Hao, H. *et al.*, 2014. "China's electric vehicle subsidy scheme: Rationale and impacts". *Energy Policy*. Vol. 73: 722-732.

Herron, D., 2013. "The business model for solar-powered electric car charging". PluginCars.com. www.plugincars.com/solar-powered-electric-car-charging-business-model-127710.html.

Holder, M., 2018a. "Amsterdam Arena switches on giant Nissan LEAF battery storage system". BusinessGreen. www.businessgreen.com/bg/news/3035094/amsterdam-arena-switches-on-nissan-leaf-battery-storage-system.

Holder, M., 2018b. "Ofgem proposes grid incentives to boost flexible electric vehicle charging and renewable power". BusinessGreen. www.businessgreen.com/bg/news-analysis/3036320/ofgem-proposes-grid-incentives-to-boost-flexible-ev-charging-and-renewable-power.

ICCT, 2017a. *Emerging best practices for electric vehicle charging infrastructure.* International Council on Clean Transportation, Berlin. www.theicct.org/sites/default/files/publications/EV-charging-best-practices_ICCT-white-paper_04102017_vF.pdf.

ICCT, 2017b. *Adjustment to subsidies for new energy vehicles in China.* International Council on Clean Transportation, Berlin. www.theicct.org/sites/default/files/publications/China-NEV_ICCT_policy-update_17052017_vF.pdf.

ICCT, 2016. *Comparison of leading electric vehicle policy and development in Europe.* International Council on Clean Transportation, Berlin. *www.theicct.org/sites/default/files/publications/ICCT_EVpolicies-Europe-201605.pdf*.

IEA, 2018a. "Electric vehicles. Tracking clean energy progress", International Energy Agency, Paris. *www.iea.org/tcep/transport/evs/* (accessed November 2018).

IEA, 2017. *Global EV outlook 2017.* International Energy Agency, Paris.

IEA, 2016. *IEA atlas of energy – Country profiles.* International Energy Agency, Paris. *http://energyatlas.iea.org/#!/tellmap/-1118783123/3* (accessed February 2018).

INRIX, 2017. "INRIX identifies top U.S. cities for shared highly autonomous vehicle deployment". INRIX. *http://inrix.com/wp-content/uploads/2017/03/INRIX-Automated-Vehicle-Study-2017_FINAL.pdf*.

Ionity, 2018. *www.ionity.eu/ionity-en.html*.

IRENA, 2019a. *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables.* International Renewable Energy Agency, Abu Dhabi

IRENA, 2019b. *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi.

IRENA, 2017a. *Electric vehicles: Technology brief.* International Renewable Energy Agency, Abu Dhabi.

IRENA, 2017b. *Electricity storage and renewables: Costs and markets to 2030.* International Renewable Energy Agency, Abu Dhabi.

IRENA, 2015. *Renewable energy target setting.* International Renewable Energy Agency, Abu Dhabi.

Jaguar, 2018. "Jaguar charges ahead with all-new electric i-PACE". Jaguar. *https://media.jaguar.com/news/2018/03/jaguar-charges-ahead-new-all-electric-i-pace*.

Karsten, J., West, D. 2018. "The state of self-driving car laws across the U.S." Brookings Institution. *www.brookings.edu/blog/techtank/2018/05/01/the-state-of-self-driving-car-laws-across-the-u-s/*.

Kasten, P., Bracker, J., Haller, M., 2016. *Electric mobility in Europe – Future impact on the emissions and the energy systems*. Öko-Institut e.V. & Transport and Mobility Leuven, Berlin.

Kempton, W., 2016. *Grid-integrated vehicle implementation: Learnings and looking ahead. www.ceem-dauphine.org/assets/dropbox/Kempton-Dauphine-ImpactEVs.pdf*.

Kensington and Chelsea, 2017. "Kensington and Chelsea Council, OVO and ubitricity join forces to expand London's first lamp post electric vehicle charging network". The Royal Borough of Kensington and Chelsea. *www.rbkc.gov.uk/press-release/kensington-and-chelsea-council-ovo-and-ubitricity-join-forces-expand-london%E2%80%99s-first*.

Koetsier, J., 2017. "Surprise: 70% of millennials do not want electric vehicles". *Forbes*. *www.forbes.com/sites/johnkoetsier/2017/04/17/surprise-70-of-millenials-do-not-want-electric-vehicles/#27d-fe143f66b*.

Laborelec, 2017. "SMATCH – cost-effective EV charging management". *www.laborelec.be/ENG/smatch-cost-effective-ev-charging-management/*.

L'Agence nationale de la recherche, 2016. Projet Helios.

Lambert, F., 2016. "BMW and Bosch open new 2.8 MWh energy storage facility built from batteries from over 100 electric cars". Electrek. *https://electrek.co/2016/09/22/bmw-bosch-energy-storage-facility-built-from-batteries-from-over-100-electric-cars/*.

Laurischkat, K., Viertelhausen, A., Jandt, D., 2016. "Business models for electric mobility". *Procedia CIRP*, Vol. 47: 483-488.

Leemput, N., 2015. *Grid-supportive charging infrastructure for plug-in electric vehicles*. PhD thesis. University of Leuven.

Lévay, P.Z., Drossinos, Y., Thiel, C., 2017. "The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership". *Energy Policy*, Vol. 105: 524-533.

Lienert, P., 2017. "Self-driving costs could drop 90 percent by 2025, Delphi CEO says". *Reuters. www.reuters.com/article/us-autos-delphi/self-driving-costs-could-drop-90-percent-by-2025-delphi-ceo-says-idUSKBN1DY2AC*.

Living Lab Smart Charging, 2017. www.livinglabsmartcharging.nl/nl/.

Loveday, E., 2017. “China approves NMC battery technology for green car subsidies”. InsideEVs. https://insideevs.com/china-nmc-battery-technology-green-car-subsidies/.

Manthey, N., 2018. “Brussels bans diesel from 2030”. electrive.com. www.electrive.com/2018/06/02/brussels-bans-diesel-from-2030/.

Mauri, G., Valsecchi, A., 2012. “The role of fast charging stations for electric vehicles in the integration and optimization of distribution grid with renewable energy sources”. CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid.

McKenzie, K. *et al.*, 2016. “Electrified transportation as a power grid resource”. IEEE Transportation Electrification Conference and Expo, Dearborn, Michigan. www.hnei.hawaii.edu/sites/www.hnei.hawaii.edu/files/2016%20ITEC%20IEEE%20Electrified%20Transportation.pdf.

McKinsey, 2018. *The global electric-vehicle market is amped up and on the rise.* McKinsey & Company. www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-global-electric-vehicle-market-is-amped-up-and-on-the-rise.

McKinsey, 2014. *Electric vehicles in Europe: Gearing up for a new phase*. McKinsey & Company and Amsterdam Roundtables Foundation, Amsterdam.

Muratori, M., Rizzoni, G., 2016. “Residential demand response: Dynamic energy management and time-varying electricity pricing”. IEEE Transactions on Power Systems, Vol. 31(2): 1108-1117.

Navigant Research, 2016a. Electric drive buses. Navigant Research.

Navigant Research, 2016b. Electric drive trucks. Navigant Research.

Navigant Research, 2016c. Market data: Electric vehicle market forecasts. Navigant Research.

Needell, Z.A. *et al.*, 2016. “Potential for widespread electrification of personal vehicle travel in the United States”. *Nature Energy*, Iss. 1.

NextKraftwerke, 2018. "Next Kraftwerke and Jedlix launch initiative to use electric car batteries for grid stability". www.next-kraftwerke.com/news/next-kraftwerke-jedlix-launch-initiative-to-use-electric-car-batteries-for-grid-stability.

NewMotion, 2018. “The future of EV charging with V2X technology”. NewMotion. https://newmotion.com/en/drive-electric/v2g-charging-next-generation-technology.

Nhede, N., 2018. “Excel Energy to pilot level-2 EV charging in consumer homes”. Smart Energy. www.smart-energy.com/industry-sectors/energy-grid-management/excel-energy-ev-charger/.

Nissan, 2018. “Nissan launches Nissan Energy Solar: The ultimate all-in-one energy solution for UK homes”. https://uk.nissannews.com/en-GB/releases/release-426215639.

Noel, L. *et al.*, 2019. *Vehicle-to-Grid – A Sociotechnical Transition Beyond Electric Mobility*. Springer Nature Switzerland AG.

OICA, 2017. “World motor vehicle sales by country and type 2005-2017”. International Organization of Motor Vehicle Manufacturers. www.oica.net/category/sales-statistics/ (accessed February 2018).

Olsen, K., 2017. “How many miles does an average taxi cab driver drive yearly?” Career Trend. https://careertrend.com/how-many-miles-does-an-average-taxi-cab-driver-drive-yearly-13658842.html.

Ontario, 2018. *O. Reg. 332/12: BUILDING CODE*. Government of Ontario. www.ontario.ca/laws/regulation/120332.

OVO Energy, 2018. “EV everywhere”. www.ovoenergy.com/ev-everywhere (accessed November 2018).

OVO Energy, 2017. “Nissan and OVO announce a new collaboration to accelerate the adoption of home battery storage in the UK”. www.ovoenergy.com/ovo-newsroom/press-releases/2017/october/nissan-and-ovo-announce-a-new-collaboration-to-accelerate-the-adoption-of-home-battery-storage-in-the-uk.html.

Pasaoglu, G. *et al.*, 2013. *Projections for Electric Vehicle Load Profiles in Europe Based on Travel Survey Data.* European Commission Joint Research Centre, Petten. *https://setis.ec.europa.eu/sites/default/files/reports/Projections_for_Electric_Vehicle_Load_Profiles_in_Europe_Based_on_Travel_Survey_Data.pdf*

Pasaoglu, G. *et al.*, 2012. *Driving and parking patterns of European car drivers – a mobility survey.* European Commission Joint Research Centre, Petten. *https://setis.ec.europa.eu/system/files/Driving_and_parking_patterns_of_European_car_drivers-a_mobility_survey.pdf*.

Pascale-Louise Blyth, S., 2011. *Electric cars on the 100% renewable energy island of Samsø.* Master's thesis. Aalborg University. *https://projekter.aau.dk/projekter/files/52872570/SEPM4_2011_8.pdf*.

Perkowski, J., 2017. "How China is raising the bar with aggressive new electric vehicle rules". *Forbes*. *www.forbes.com/sites/jackperkowski/2017/10/10/china-raises-the-bar-with-new-electric-vehicle-rules/#a92230977acf*.

Pfarrherr, B., 2018. *Controlling private e-mobility charging points in public low voltage grids.* Stromnetz Hamburg, Vienna.

PG&E, 2018. "Electric vehicle (EV) rate plans". Pacific Gas and Electric. *www.pge.com/en_US/residential/rate-plans/rate-plan-options/electric-vehicle-base-plan/electric-vehicle-base-plan.page?WT.mc_id=Vanity_pevrates*.

PlanGridEV, 2016a. *Analysis and performance evaluation as basis for further recommendations.*

PlanGridEV, 2016b. *Distribution grid planning and operational principles for electric vehicle mass roll-out while enabling integration of renewable distributed energy resources.*

Porsche, 2016. "800-volt charging". *https://newsroom.porsche.com/en/technology/porsche-engineering-e-power-electromobility-800-volt-charging-12720.html* (accessed 6 August 2018).

Pyper, J., 2018. "BMW's plan to optimize EV charging with renewables on the grid". Greentech Media. *www.greentechmedia.com/articles/read/bmw-optimizing-ev-charging-renewable-energy#gs.0Fv6LQE*.

Pyzyk, K., 2017. "Atlanta passes infrastructure ordinance to support EV charging". Smart Cities Dive. *www.smartcitiesdive.com/news/atlanta-passes-infrastructure-ordinance-to-support-ev-charging/511500/*.

Ramírez Díaz, A. *et al.*, 2015. "Impact of electric vehicles as distributed energy storage in isolated systems: The case of Tenerife". *Sustainability*, Vol. 7(11): 15152-15178.

Rao, R. *et al.*, 2015. "Optimizing electric vehicle users' charging behaviour in battery swapping mode". *Applied Energy*, Vol. 155: 547-559.

RECC, 2019, "An introduction to Electric Vehicle home chargepoints", Renewable Energy Consumer Code, *www.recc.org.uk/images/upload/news_240_Consumer-Guidance-on-EV-Home-Chargepoints-14.pdf*.

Reid, G., Julve J., 2016. *Second-life batteries as flexible storage for renewable energies.* Bundersverband Erneuerbare Energie e.V. and Hannover Messe. *www.bee-ev.de/fileadmin/Publikationen/Studien/201604_Second_Life-Batterien_als_flexible_Speicher.pdf*.

Renault, 2017. "Renault preparing infrastructures for the connected car of the future, with SCOOP". *https://group.renault.com/en/news/blog-renault/renault-preparing-infrastructures-for-the-connected-car-of-the-future-with-scoop/*.

Renewables & Environment, 2017. "Renault & Powervault to reuse EV batteries in home storage. Renewables & Environment". *www.renewablesandenvironment.com/mag/renault-powervault-to-reuse-ev-batteries-in-home-storage/*.

RMI, 2016. *Electric vehicles as distributed energy ºresources.* Rocky Mountain Institute, Basalt. *https://rmi.org/wp-content/uploads/2017/04/RMI_Electric_Vehicles_as_DERs_Final_V2.pdf*.

Santi, P., 2017. Interview

Sauer, N., Stefanini, S., 2018. "Spain, Europe's second largest carmaker, plans combustion engine ban". Climate Home News. *www.climatechangenews.com/2018/11/13/spain-plans-ban-petrol-diesel-cars-fossil-fuels-subsidies/*.

Schewel, L., 2017. "4 ways big data can help with electric vehicle charger deployment". StreetLight Data. *www.streetlightdata.com/4-ways-big-data-can-help-with-electric-vehicle-charger-deployment*.

Schucht, B., 2017. "The development of e-mobility from the perspective of a German TSO". 50Hertz.

Shahan, Z., 2017. "28-40% of EV drivers have solar panels". CleanTechnica. *https://cleantechnica.com/2017/06/25/28-40-ev-drivers-solar-panels-cleantechnica-ev-report/*.

Siemens, 2017. "Desigo – the state-of-the-art building automation system". *www.siemens.com/global/en/home/products/buildings/automation/desigo.html* (accessed 2017).

SLoCaT, 2017. *E-mobility trends and targets.* Partnership on Sustainable, Low Carbon Transport. *http://slocat.net/sites/default/files/e-mobility_overview.pdf*.

Smart Cities Connect, 2017. "University of Warwick demonstrates vehicle-to-grid technology". Smart Cities Connect. *https://smartcitiesconnect.org/university-of-warwick-demonstrates-vehicle-to-grid-technology/*.

St. John, J., 2015. "How EV chargers and energy storage can make good grid partners". Greentech Media. *www.greentechmedia.com/articles/read/how-ev-chargers-and-energy-storage-can-make-good-grid-partners*.

Suh, N.P., Cho, D.H., 2017. "Wireless power transfer for electric vehicles". In: *The On-Line Electric Vehicle*. Springer.

Sullivan, M., 2018. "The little company that's bringing wireless charging to electric cars". Fast Company. *www.fastcompany.com/40533008/the-little-company-thats-bringing-wireless-charging-to-electric-cars*.

Taibi, E., Fernández, C., 2017. *The impact of electric vehicles deployment on production cost in a Caribbean Island country.* IRENA Innovation and Technology Center (IITC), Bonn.

Taljegard, M., 2017. *The impact of an electrification of road transportation on the electricity system.* Chalmers University of Technology, Gothenburg.

TBC, 2017. *Battery packs of modern xEVs report.* Total Battery Consulting.

Tesla, 2018. "Tesla semi". *www.tesla.com/semi* (accessed March 2018).

The Climate Group, 2017. "Multinationals launch global program to speed up switch to electric vehicles". *www.theclimategroup.org/news/multinationals-launch-global-program- speed-switch-electric-vehicles*.

Tractebel, 2018. Internal studies. Tractebel, Brussels.

Tricoire, J-P., Starace, F. 2018. "These 3 elements are crucial for the future of electric cars". World Economic Forum. *www.weforum.org/agenda/2018/02/mobility-future-electric-cars-fourth-industrial-revolution/*.

Turpen, A., 2016. “California to get utility-owned EV charging stations with dynamic pricing”. New Atlas. https://newatlas.com/california-electric-car utility-charging/41585/.

UCS, 2017. *Accelerating US leadership in electric vehicles.* Union of Concerned Scientists, Washington, D.C. www.ucsusa.org/sites/default/files/attach/2017/09/cv-factsheets-ev-incentives.pdf?_ga=2.108452610.1630188791.1517413160-1434713090.1436805699 [accessed November 2018].

UITP, 2016. *ZeEUS eBus report: An overview of electric buses in Europe.* ZeEUS project. http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-internet.pdf.

UK Government, 2016. “Grant schemes for electric vehicle charging infrastructure”. www.gov.uk/government/collections/government-grants-for-low-emission-vehicles (accessed January 2018).

V2G Clarity, 2017. *IEC 63110 – Standardizing the management of electric vehicle (dis-)charging infrastructures.* www.v2g-clarity.com/en/blog/iec-63110-standardizing-management-of-ev-charging-infrastructures/.

Van den steen, F., 2018. “Cities’ policies push electric vehicles”. Global Fleet. www.globalfleet.com/en/safety-environment/global/analysis/cities-policies-push-electric-vehicles.

Vattenfall, 2017. “Vattenfall is switching its whole car fleet to electric vehicles”. https://corporate.vattenfall.com/press-and-media/press-releases/2017/vattenfall-is-switching-its-whole-car-fleet-to-electric-vehicles/.

Virta, 2017. “Public bidirectional EV charging point installed to Finland”. www.virta.global/news/the-first-public-bidirectional-ev-charging-point-to-finland.

Wallbox, 2018. www.wallbox.com (accessed January 2018).

Weiller, C., Sioshansi, R. 2016. “The role of plug-in electric vehicles with renewable resources in electricity systems”. *Revue d* économie *industrielle*, vol. 148: 291-316.

Wenyu, S., 2017. “China builds world’s largest EV charging network with 167,000 stations”. People’s Daily Online. http://en.people.cn/n3/2017/0906/c90000-9265487.html.

WHO, 2018. “Air pollution”. World Health Organization, Geneva. www.who.int/airpollution/ambient/en/.

Xcel Energy, 2015. “Electric vehicle charging station”.

ANNEX 1: Incentives to deploy EVs and charging infrastructure

Direct monetary incentives for EVs

Financial and fiscal (related to government revenue and taxes) monetary incentives aim to encourage the purchase of EVs through one-time subsidies as well as to reduce their ownership costs. The most common types of financial and fiscal practices include:

- *Purchase subsidies or grants*: This type of incentive gives direct monetary incentives to support the purchase of EVs, the replacement of commercial or public sector fleets by EVs and the installation of EV charging services. The subsidies or grants are usually part of the government budget to promote sustainable mobility and are renewed and revised each year.

- *Scrappage schemes*: Conducted by governments, multiple variations of this type of incentives exist across the world, but the underlying mechanism is to scrap an old contaminating vehicle in exchange for getting a discount when purchasing a new one with better environmental performance.

- *Electricity rates*: Utilities offer commercial or private customers discounts on electricity rates for charging their BEVs or PHEVs, which lowers the total cost of EVs.

- *Tax exemption or reduction*: This includes a wide range of incentives with the goal of reducing the fiscal costs of purchasing a new vehicle. In this sense, EVs can be exempt from value-added tax (VAT), registration taxes, road circulation taxes, vehicle ownership taxes and purchase taxes, among others.

- *Income tax credit*: In this type of incentive, businesses or private customers that have installed electric charging equipment or purchased new alternative fuel vehicles might be eligible to receive an income tax credit worth a given percentage of the total costs of the investment, or else equal to a given calculated credit. The concept is similar to the purchase subsidies; however, it differs in the way of receiving the money. In this case, the credit is returned to the beneficiary at the time of the annual tax declaration.

Case studies: Direct monetary incentives for EVs in France and China

France has relied on a bonus-malus system that offers a grant for purchase of a low-polluting vehicle and has placed a penalty on the purchase of a high-polluting vehicle since 2008. The subsidy covered 27% of the purchase price or up to EUR 6 300 for a BEV, and 20% or up to EUR 4 000 for a PHEV. The incentive proved to be effective as the number of sales increased year on year. In April 2015 EV sales in France surged and surpassed the 1% market penetration rate. This was the result of the introduction of a scrappage scheme of EUR 3 700 on top of the bonus-malus system. As of April 2015 users scrapping a diesel car and purchasing an EV could benefit from a fiscal incentive of EUR 10 000 for a BEV and EUR 7 700 for a PHEV (Lévay *et al*., 2017).

Over the years the Chinese central government has offered substantial funding to support the purchase of EVs under the Electric Vehicle Subsidy Scheme (EVSS) launched in 2009. In the beginning, the subsidies were available only for public procurement, but an extension in 2010 made private customers eligible for the grants as well. The scheme covered a wide range of vehicle types: buses, freight trucks and passenger cars.

For the latest category, China's initial EVSS lasted until the end of 2012 and provided up to CNY 50 000 for a PHEV and CNY 60 000 for a BEV depending on the rated power, electric range and battery energy density. The scheme was renewed for the period 2013 to 2015 with an updated subsidies amount of CNY 35 000 for a PHEV and between CNY 35 000 and CNY 60 000 for a BEV. In 2016 the scheme was extended again for the period 2016 to 2020, and the phase-out of the subsidy programme was set for 2021. To complement the one-time subsidies, in 2014 the Chinese government announced the exemption of EVs from the 10% purchase tax (Hao *et al*., 2014; ICCT, 2017b; Perkowski, 2017).

Non-monetary incentives for EVs

In addition to e-mobility targets and collective agreements led and supported by country governments and organisations, the most common non-monetary incentives implemented by local authorities include:

- *Driving permissions*: As low-pollution vehicles, EVs can be exempted from driving restrictions in city centres, can benefit from road toll exemptions or discounts, and can be allowed to circulate in designated reserved lanes for public transport.
- *Parking permissions*: EV users can have priority when applying for a parking permit or can benefit from free parking.
- *Free charging*: EV users can be entitled to recharge their batteries for free in indicated locations.
- *Emissions test exemption*: A common practice in the US is to exempt BEVs and PHEVs from emissions inspections.

Case studies: Indirect (non-monetary) incentives in selected countries

China: A common practice to reduce air pollution and limit traffic congestion in China is to enforce road restrictions depending on the last digit of a vehicle licence plate number. The cities of Beijing and Tianjin have exempted EVs from this practice, allowing the vehicles to circulate regardless of the day and time (Van den steen, 2018).

Germany: Under the federal electric mobility regulation, approved in 2015, municipalities are entitled to grant special benefits to low-emission or electric vehicles. Privileges include free or preferential parking, access to high-occupancy vehicle lanes and access to restricted traffic zones. The regulation applies to the whole country; however, it gives municipalities the responsibility to design and implement the incentives. Stuttgart, for example, provides free parking for EVs in public parking spaces (ICCT, 2016).

The Netherlands: In the Netherlands there are no non-fiscal incentives planned at the national level; however, many municipalities have outlined their own strategy on indirect incentives. In Amsterdam, for example, EV drivers have priority access to parking permits and also have reserved parking slots near charging stations (ICCT, 2016).

Norway: As the country with the highest EV penetration in the world, Norway has been offering non-monetary benefits to EV users for many years. Although these privileges are implemented by municipalities and can differ from city to city, the government regulates the subsidies at a national level. Drivers of BEVs have free access to toll roads, benefit from reduced ferry rates, are allowed to circulate in bus lanes, and can charge and park their vehicles for free at public premises. EVs are also labelled with a special registration plate (ICCT, 2016).

ANNEX 2: Status of EV battery and charging station technologies

Suitability of EV storage technologies to provide grid services

Around 300 full charging cycles per year are necessary for a battery to provide system-wide balancing or behind-the-meter optimisation through the absorption of excess renewable electricity, for limiting fluctuation. A high depth of discharge (DoD) tolerance is required. All types of lithium-ion batteries are the best suited today. However, redox flow battery technology, with its long cycle life, is able to undergo high DoD and can provide this service. Lithium-metal-polymer (LMP) could be suited in terms of DoD but faces limitations due to high temperature and high self discharge. ZEBRA technology is not able to reach 100% of DoD and cannot be envisaged here.

For *time-of-use application*, where the consumer can be asked to shift his/her consumption, energy is more important than power. Because energy and power can be scalable independently for redox flow batteries, they would be suited in this type of situation. Li-ion technology is also well suited for this application.

Ancillary services are used to balance the electricity grid – that is, to keep the grid frequency around the reference (50 hertz in Europe and 60 hertz in the US). These services can be acquired by procurement in reserve markets (where in place), which can be divided into primary reserve, secondary reserve and tertiary reserve[9].

- For primary reserve, DoD and battery involvement is smoother than for renewables balancing. When the frequency drops, the battery must inject power (and vice versa). To do so, the referenced battery state of charge remains around 50% and will fluctuate in a narrow band around this level. For example, in Belgium approximately 1.5 full equivalent cycles must be considered each day. These full equivalent cycles consist of multiple cycles with low DoD, which are more conservative for the technology ageing. Frequency gaps appear less often, and batteries can be used with a C-rate lower than 1C (for both charge and discharge).

- For secondary reserve, the reaction time needed is slower and the amount of cycles required is lower compared to frequency containment reserve (FCR).

- For tertiary reserve, the reaction time needed is slower and the number of cycles required is lower, even compared to automatic frequency restoration reserve (aFFR). The energy needed is higher (lower C-rate) compared to FCR and aFRR.

Li-ion and redox flow batteries can be used for this purpose, as this application is less rough for batteries. LMP suffers from the same constraints as renewable storage (maintaining a high-temperature environment), and its use in this application has to be confirmed.

For *back-up application* (lowering the dependence on the electricity grid and reducing the energy bill by charging cheap electricity at off-peak hours), the relevance of a battery has been proven. The frequency of cycling is dependent on the grid reliability, but the profile remains the same: the battery has to face long state of charge duration and to support deep DoD, as for renewable balancing, but long standby times with full state of charge are also possible.

Li-ion is often not the best suited in this type of situation, as these batteries will age more quickly in a charged state (not stable) compared to lead-acid batteries. To use Li-ion for back-up for a long time, the battery would have to be kept partially charged, not completely charged, to keep the chemistry sTable and to prevent any runaway or drastic capacity decrease (thus using the battery at only a portion of its capabilities). Even

---

[9] Also called R1, R2 and R3 or Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR) in Europe.

though lead-acid does not perform cycling as well as Li-ion, it can be maintained at a high state of charge for a long time without ageing.

Power charging levels and modes

The three commonly distinguished levels of power output (terminology used mainly in North America) are:

- Level 1 chargers (AC ≤ 3.7 kW) are devices installed in private households, the primary purpose of which is not recharging EVs.
- Level 2 chargers (AC > 3.7 kW and ≤ 22 kW) are installed mainly in public or private places.
- Level 3 chargers (AC or DC > 22 kW) are installed mainly along highways.

in Europe, Levels 1 and 2 are referred to as slow chargers, and Level 3 is referred to as fast chargers. In North America, the three levels are defined in SAE J1172.

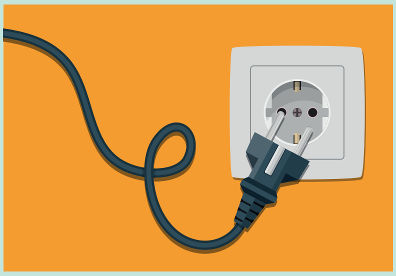
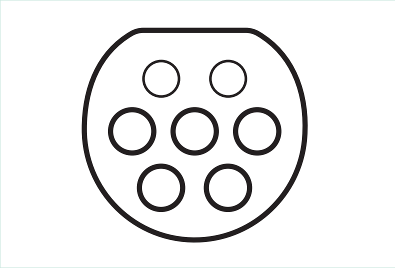
Mode is a concept from a standard that refers primarily to the required electric protection system, which is linked to power range. IEC61851-1:2017 defines four charging "modes" for cable charging that differ in terms of functionalities. The technical specifications of the different charging modes, including types of sockets and connectors used, are provided in Table 20.

For Mode 3, there are three types of plugs defined in IEC 62196:

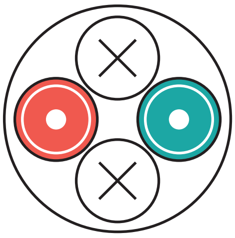
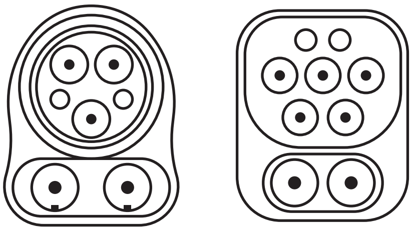
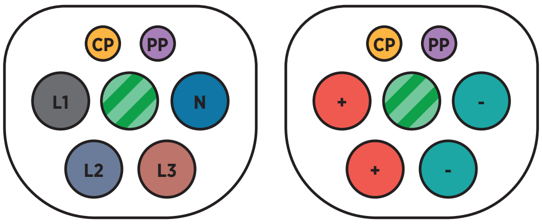
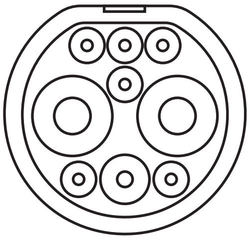
- Type 1, also known as the "Yazaki plug" and defined in SAE J1772. It is used in North America and Japan.
- Type 2, also known as the "Mennekes plug". It is a plug recommended by the EU.
- Type 3 is now obsolete. It was promoted in the past in France and Italy.

Additionally, China is using GB/T 20234.2 for Mode 3.

Table 20: Charging modes in detail and corresponding types of sockets and connectorss

Mode 1	Mode 2	Mode 3
		
Connection of an EV to a standard socket-outlet of an AC supply network	Connection of an EV to a standard socket-outlet of an AC supply network	Connection of an EV to AC EV supply equipment permanently connected to an AC supply network
No supplementary pilot or auxiliary contacts	Cable with control pilot and personal protection against electric shock	Control pilot function extends from the AC EV supply equipment to the EV
Max. 16 A per phase, 1- or 3-phase	Max. 32 A per phase, 1- or 3-phase	Max. 63 A per phase, 1- or 3-phase; in general, EVSEs do not exceed 32 A per phase
In most countries, this solution is not recommended, and is sometimes prohibited or limited to a lower current	Prohibited for public charging or limited to lower currents in some countries	The most secure AC charging solution

Mode 4:
Connection of an EV to an AC or DC supply network utilising DC EV supply equipment.
Control pilot function extends from the DC EV supply equipment to the EV.
Max. 200 kW today, with 350 kW announced.

CHAdeMO	CCS1/2
International standard of Japanese origin, published by major standardisation organisations (IEC, IEEE, EN and JIS); identical plugs worldwide. Used by Japanese, Korean and some European automakers. Typically 50 kW today, but CHAdeMO Association has already increased up to 400 kW in its latest edition.	US/European industrial standard, of which CCS2 is mandated by the EU as the minimum requirement (all Mode 4 charging solutions should at least implement one CCS connector in the EU). Typically 50 kW today, but some new models such as Jaguar I-PACE, and Audi e-Tron can charge at higher power (100-150 kW). The first 350 kW chargers were being deployed in 2018, *e.g.*, in the Ionity project (Ionity, 2018).
	
Tesla	**GBT**
Proprietary charging technology compatible with Tesla cars at Superchargers; typically 120 kW today. Same connector pins for DC and AC charging but the US/EU plugs are different	In China, for Mode 4, GB/T 20234.3, is used (CharIN, 2018b).
	

Charging technologies outlook

Table 21: Overview of the charging solutions for cars and heavy-duty vehicles (typically buses)

	PHEV car	BEV car	PHEV bus	BEV bus
Cable charging 3-50 kW	Mature		Mature Used for depot charging at 50 kW.	
Cable charging 100 kW	Under development	Under development 150 kW expected for 2017-2018 Mainly needed when long range is needed (*e.g.*, highway)	Under development	Under development Potentially useful for relatively long stops (10 minutes)
Static wireless charging 3-22 kW	Emerging Pilots from OEMs Available with retrofit Fleet use expected in 2018; commercialisation (luxury) cars expected for 2019 Limited standardisation		Low maturity Pilots	
Static wireless charging > 50 kW	Under consideration		Currently limited number of commercial lines; potential growth	
Dynamic wireless charging	Very limited number of pilots; limited growth potential		Limited number of pilots; expensive	
Pantographs (100 kW - 1 MW)	Not available		Currently commercial lines; moderate potential growth	
Battery swapping	Former projects; deprecated		Very limited number of pilots in Asia; very limited potential because of high complexity and cost	
Overhead lines	NA ICE motor could be used as back-up	Deprecated	Declining	
Ground rail	R&D			

ANNEX 3: Business models for EV charging service providers

The **charging service provider** model includes the installation and maintenance of public and/or private charging stations for customers. Some sub-models include the manufacturing and/or supply of the charging points themselves and the provision of adjacent services. For private charging, the customer pays for the charging point, and energy is sold in the contract. For public charging, public financing has proven efficient to limit the high upfront capital cost, with the main revenue stream also coming from recharging.

The major players in the market are power utilities, technology companies and specialised independent companies:

- *Utility companies* focusing on the installation and operation of charging points.

  Examples include German utilities (E.ON, Vattenfall, innogy, EnBW) owning over 35% of public charging infrastructure in Germany, and Fortum's Charge & Drive programme in Finland. In Norway, utility-owned Grønn Kontakt operates a nationwide DC fast-charging network of 140 chargers, with Statkraft as a major shareholder. In some cases, distribution system operators could install and operate charging points (*e.g.*, the Elaad association in the Netherlands [10]).

  The world's largest charging network is run by State Grid of China (Wenyu, 2017), which had a monopoly to manage and supply charging stations but more recently has opened the market to competition from private players (BusinessWire, 2016). With many new EV models to be introduced in the market in 2018/19, further large-scale roll-outs of charging stations are planned, for example by Enel in Italy and by E.ON and Clever, a group of five Danish utilities (Table 8).

- *Large technology companies* (such as Bosch and Schneider Electric), for which the manufacturing of charging stations represents only a small part of their portfolio.

  Specialised independent companies, with a variety of sub-models, that manufacture and/or install and operate charging points and provide related services such as maintenance support and cloud data services.

  The most typical is the "own and operate" model, often combined with a software-as-a-service (SaaS) offering. For example, periodic software updates and subscriptions for smart charging are often offered (*e.g.*, by the two biggest European charging station operators EVBox and NewMotion).

  An alternative model, developed by ChargePoint, covers about 70% of the US market. ChargePoint sells a turnkey solution that combines hardware, low fixed assets (they do not own their stations) and service-based revenue (SaaS). All ChargePoint charging stations are Internet connected (3G or 4G) with real-time ability to manage the stations from anywhere in the world, which is not commonplace. Sub-models based on other revenue streams such as advertising also exist (*e.g.*, California-based Volta).

This market has recently experienced substantial consolidation. In 2017 ENGIE acquired EVBox, and several oil companies – initially looking for synergies between traditional petrol stations and eventually for new business models – have shown interest in EV charging. In 2017 Shell purchased NewMotion, Europe's largest electric charging point operator with a network of 80 000 sites.

---

[10] Not part of the regulated asset base of regulated operators in Europe.

ANNEX 4: Expected developments in EV technology

Cost and competitiveness of EVs

Currently EVs are not cost competitive compared to equivalent ICE vehicles because of their higher upfront costs, caused by high battery costs today.

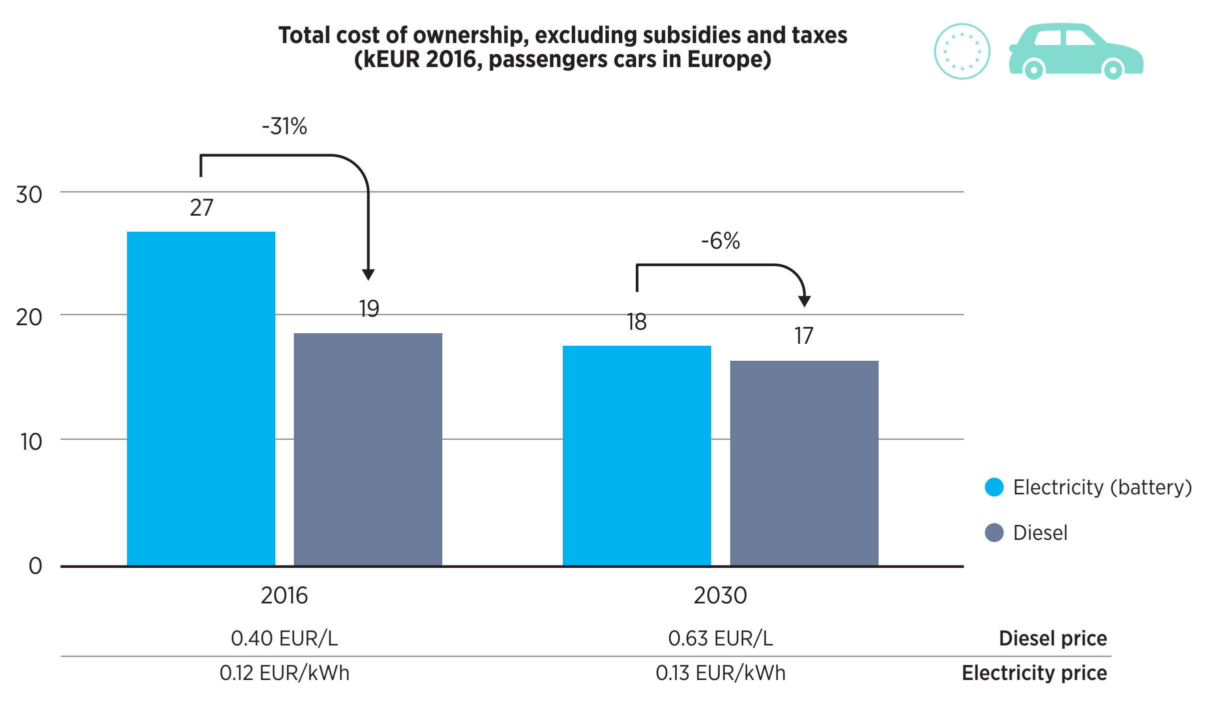
In the medium term, unsubsidised total cost of ownership (TCO) parity is likely to arrive and make EVs competitive on a lifetime cost basis. The margin will still be limited, and the competitiveness of one choice or another will be very sensitive to the yearly mileage.

Figure 40 shows that, without subsidies and tax breaks, a diesel vehicle was 31% cheaper in 2016 than the equivalent EV. In 2030 diesel vehicles will be only 6% cheaper.

Three major trends and factors are behind this trend: the reduction in EV capital expenditure (CAPEX), rising diesel prices and the average distance driven with the vehicles. The regulatory regime also must be examined to provide a full picture.

First and foremost, the total cost of ownership economics of EVs is driven by their higher purchasing price. In 2016 a typical EV passenger car cost approximately 25% more than its diesel equivalent (CEEME, 2016a). Although an EV is cheaper to operate due to lower electricity price per km (versus diesel), the savings realised on fuel currently do not offset the higher CAPEX. Much of the 30% decrease in the EV total cost of ownership presented in Figure 43 is due to a decrease in EV CAPEX, which is in turn driven by a decrease in battery CAPEX.

Figure 40: Present and future total cost of ownership (TCO) for electricity- and diesel-powered vehicles



Source: Tractebel, 2016.

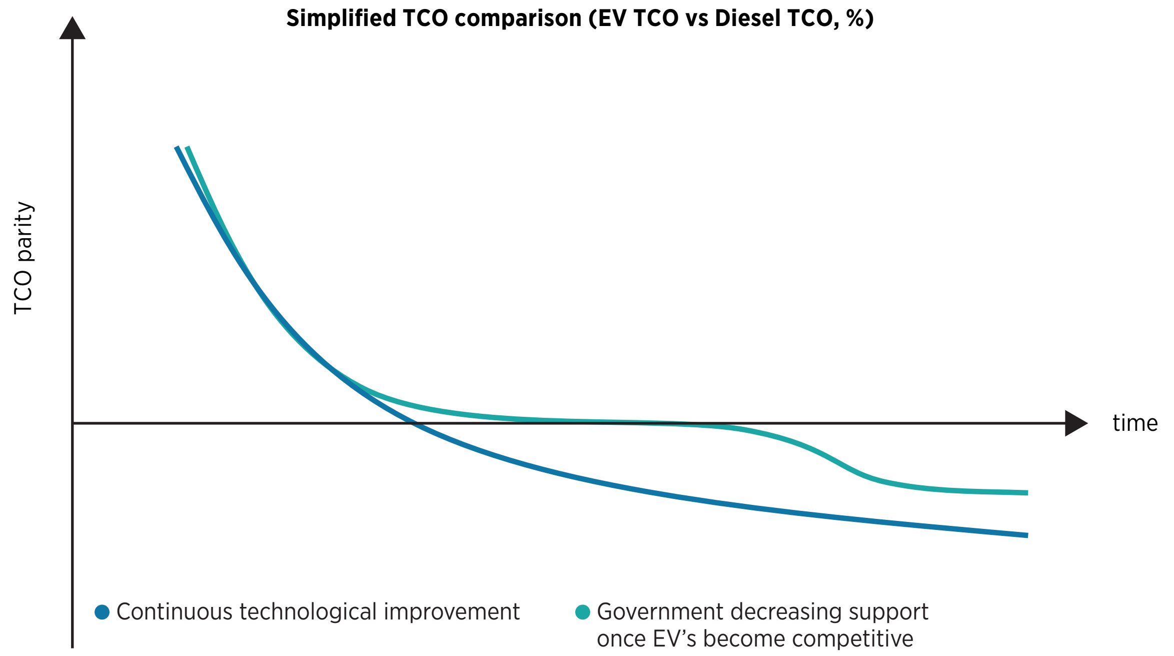
Given that batteries represented 40% of the cost of a new EV in 2016 (CEEME, 2016a), this sharp decrease in battery costs greatly improves the overall EV CAPEX. In the meantime, the CAPEX for diesel vehicles – a mature technology – is expected to remain sTable between 2016 and 2030.[11]

With regard to a vehicle's operational costs, two factors will be important to look at: the evolution of fuel costs and the distance driven by the vehicle. As shown in Figure 40, the average price of electricity is expected to increase slightly by 2030, while the price of diesel is expected to increase by more than half. While the impact of fuel costs on a vehicle's total cost of ownership will depend on the distance driven by the vehicle – and hence the amount of fuel purchased – this trend does point to making EVs more competitive by 2030 than they are today. The total cost of ownership comparison shown in Figure 40 was made for an average driver (20 000 km per year)(BNEF and McKinsey, 2016).

Lastly, depending on the speed and fashion with which governments choose to decrease their support for EVs, a period could appear during which the improving economics of EVs are dampened by decreasing subsidies. While many have observed a continuous improvement of the economics of EVs, and while EVs are predicted to become close to competitive by 2030 (Figure 41), subsidies and financial advantages will change the picture. In addition, diesel will likely face even stricter regulation that will lower its attractiveness.

Compared to a subsidies-free scenario, this analysis assumes that EVs will become competitive much sooner than 2030. However, once EVs become attractive, governments may choose to accelerate their current efforts to ramp down regulations. A transition period may thus appear during which EVs and diesel vehicles are exactly competitive as governments ramp down their support for EVs. In the longer term and once all support has been phased out, the total cost of ownership for EVs could start to improve again.

Figure 41: Scenarios for simplified total cost of ownership (TCO) comparison (electric versus diesel vehicles)



---

[11] CAPEX for diesel vehicles *expressed in real terms* is expected to remain stable between 2016 and 2030.

EV batteries

A significant share of global battery production is for mobility purposes, and this trend might continue in the coming years. The choice of battery technology for different mobility applications is based on price considerations, safety level, and energy and power performance required. Capacity and other technical features of batteries are among the key factors for determining the availability of EVs.

Over time, battery energy density – that is, the amount of energy stored in a given system or region of space per unit volume – has increased. This phenomenon is due in part to cell and pack design optimisation (for example, optimisation of temperature dissipation by changing the cell shape), but the principal factor is the nature of the material used as the electrode in the battery.

Lithium-ion is a prevalent technology today, regardless of the subchemistry. It is suiTable for both mobility and grid applications, and the economics are increasingly favourable. A limited variety of battery subchemistries is used today in Li-ion batteries. The choice of battery technology is a compromise between safety, cost and performance.

As highlighted in Table 22, it is mainly the type of positive electrode that drastically improves the cell performance in terms of energy density. The key available sub-technologies used for the positive electrode are based on LFP (lithium-iron-phosphate), NMC (nickel-manganese-cobalt) and NCA (nickel-cobalt-aluminium). NCA, even if it presents very high energy (and power) densities compared to the two others, has low safety as is not sTable in the face of high temperature. Detailed technical comparison between the two chemistries used the most in mobility, LFP and NMC, is provided in Table 23. While LFP is safer, cheaper and has longer lifetime, NMC has higher capacity and power.

A comparison of Li-ion battery subchemistries used in representative light-duty vehicle models is provided in Table 24.

The electric bus market is dominated by China, with 75% of the bus batteries produced locally. The most commonly used subchemistries are LFP. NMC batteries are largely manufactured and used elsewhere (Dodgson, 2016). LFP appears to be the best compromise between safety, performance and cost. The idea was even debated to ban NMC from mobility applications in China for safety reasons (even though it is less dangerous than NCA) for the benefit of LFP (Deutsche Bank, 2016). However, other sources mentioned a subsidy programme for NMC batteries for EVs (Loveday, 2017).

Energy density decreases from the cell to the pack level. A cell installed in a car today can achieve 250 Wh/kg while the energy density of the pack is only 140 Wh/kg (FEV, 2017; TBC, 2017). A car equipped with such a battery can drive for around 400 km and can be recharged up to 80% in 30 minutes (with fast charging that accelerates ageing). The target for 2020 for academic projects such as the French project Helios (L'Agence nationale de la recherche, 2016) is to achieve a cell energy density of 300 Wh/kg and a battery pack energy density of 200 Wh/kg. This increase could lead to ranges of around 550 km.

Table 22: Comparison between the main chemistries of lithium-ion batteries

	LCO*/ Graphite	LMO**/ Graphite	LFP/ Graphite	NMC/ Graphite	NCA/ Graphite	Oxide positive/ LTO***
Energy density (Wh/kg) at cell level	120-190	105-180	80-160	110-220	80-260	80-100
Energy density (Wh/L)	250-640	250-350	220-320	325-400	210-700	< 170

** lithium-cobalt-oxide ** lithium-manganese-oxide *** lithium-titanate-oxide*

Table 23: Comparison between LFP and NMC lithium-ion battery technologies

Li-ion battery chemistry	LFP	NMC
Maximal C-rate in charge	3C	1-2C
Nominal C-rate in charge	0.5-1C	0.5C
Cycle life	Up to 10 000 (100% DoD, 70-80% EoL, 25 °C)	Up to 5 000 (80% DoD, 80% EoL, 25 °C)
Typical warranty	10 years (100% DoD, 60% EoL) Note: C-rate is not mentioned	10 years (100% DoD, 60% EoL) Note: C-rate is not mentioned
Round trip efficiency (DC) at cell level	< 90%	94-99%
Advantages	High safety compared to other Li-ion systems. Longer lifetime than NMC. Lower cost.	High capacity and power compared to LFP.
Main issues	Low energy density compared to NMC. Increases the size of system to reach an energy comparable to NMC.	Lower safety compared to LFP. Higher sensitivity to high temperatures. Shorter lifetime than LFP. Higher cost.

Table 24: Comparison of selected electric cars by battery type and capacity, range and charge time

Car supplier	BMW	Chevrolet	Mitsubishi	Nissan	Tesla
Model	I3	Chevy Volt	i-Miev	LEAF	Model S
Battery chemistry	LMO/NMC (22 kWh, 204 kg)	LMO/NMC (16 kWh, 181 kg)	NMC (16 kWh; 147 kg)	LMO (30 kWh, 272 kg)	NCA (90 kWh, 540 kg)
Range (km)	130-160	64	128	250	424
Charge time	~4 hours at 230 V AC, 30 A; 50 kW Supercharger; 80% in 30 minutes	10 hours at 115 V AC, 15 A; 4 hours at 230 V AC, 15 A	13 hours at 115 V AC 15 A; 7 hours at 230 V AC 15 A	8 hours at 230 V AC, 15 A; 4 hours at 230 V AC, 30 A	9 hours with 10 kW charger; 120 kW Supercharger, 80% charge in 30 minutes

Based on Battery University, 2018; ENGIE, 2017.

The battery capacity decreases over time and cycling. For any mobility application, the battery has to be replaced (reaches its "end of life") when it reaches 70% of initial capacity, at which point the decrease can accelerate drastically. Car and bus manufacturers have placed considerable attention on the ageing of batteries for mobility. If the battery is cycled in smoother conditions (cycling rate/charging speed, temperature, depth of discharge and state of charge used), it will last longer than if it is asked to deliver at the maximum of its capacity.

An efficient cooling system is needed to maintain a constant temperature around the battery so that the maximum lifetime can be reached and safety is obtained. NMC is more sensitive to temperature compared to LFP, and it will age more rapidly if temperature is higher during its lifetime. NMC is also more sensitive to the cycling rate applied (this subchemistry has a lower nominal cycling rate).

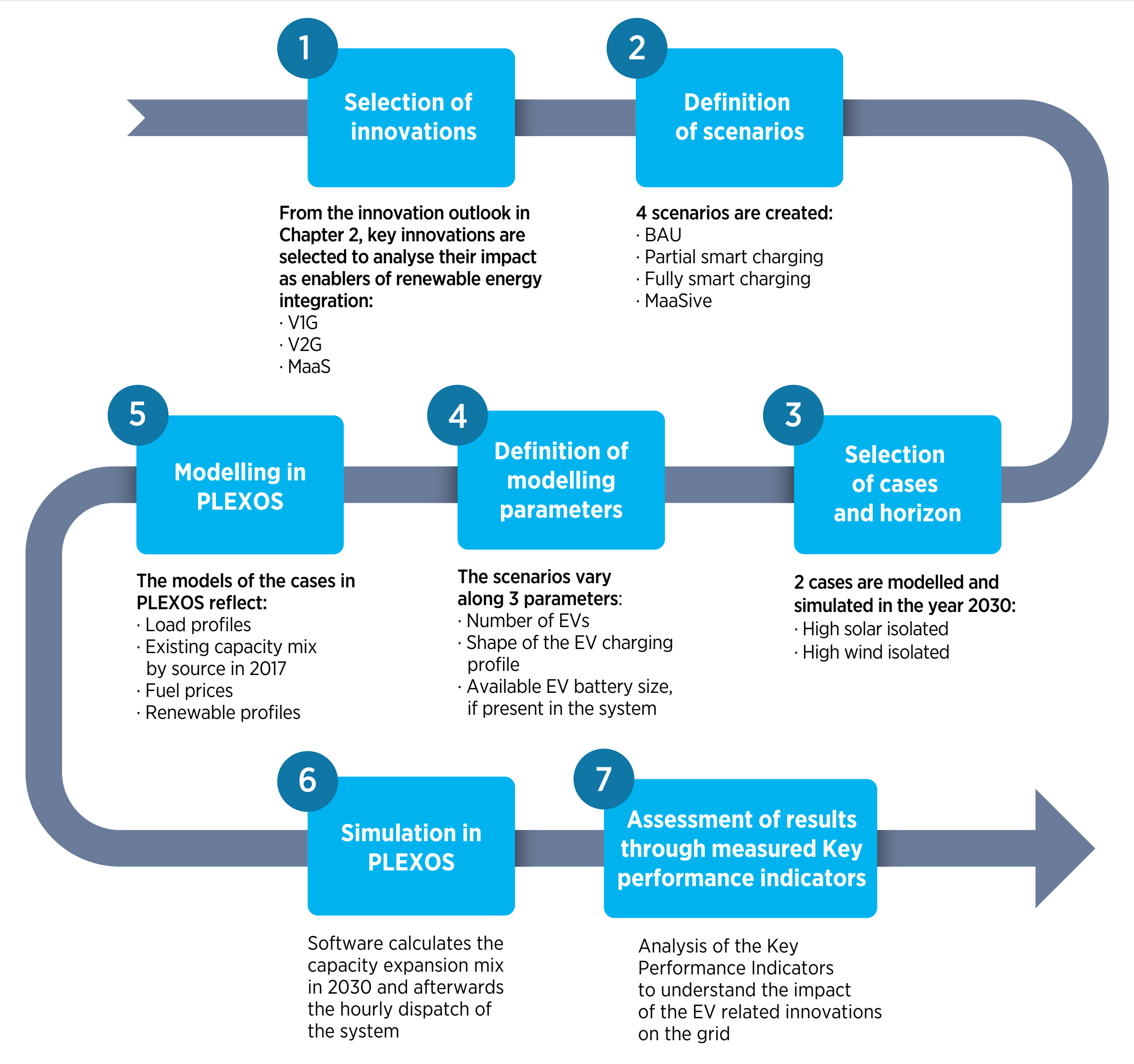
ANNEX 5: Modelling methodology

Key elements of modelling methodology

The goal of the modelling was to analyse the impact of integrating EVs in high-renewable energy systems in a variety of situations that differ not only in the level of development in the power and transport sector but also with regard to the predominant renewable source in the electricity mix. The modelling methodology is explained in the seven steps of Figure 42.

Two isolated systems, one with a high solar share and one with a high wind share in power generation, were selected for the study. These systems were simulated

Figure 42: Modelling methodology



under four alternative scenarios that contemplate different levels of innovations in the power sector (uncontrolled charging, V1G and V2G scenarios) and in the transport sector (so-called MaaSive scenario). The study plays with three key EV modelling parameters to mirror the implications of the adoption of the innovations corresponding to these scenarios: number of EVs in the system, shape of the EV charging load and available EV battery size. Box 14 defines these scenarios and how they were modelled in detail.

BOX 14: MODELLING OF EVS IN PLEXOS

The modelling of EVs in PLEXOS varies correspondingly to the innovations assumed in the four scenarios. These variations are mirrored in the following three modelling parameters:

1. Number of EVs in the system
2. EV load profile of charging needs
3. Mobility patterns and available battery capacity for flexibility services.

The innovations on the power system – *i.e.*, **V1G and V2G are reflected in the shape of the EV load profiles and in the possible utilisation of EV batteries to provide grid flexibility services. MaaS adoption influences the number of EVs, the mobility patterns and the availability of EV batteries.**

Table 25 summarises the implications of assuming innovation in MaaS, and Figure 43 and Figure 44 illustrate how EVs will be used during the day for each of the cases.

Table 25: Implications of innovation in mobility-as-a-service

INNOVATION IN MAAS	
NO	**YES**
Vehicle ownership rates and yearly mileage of cars will stay at current values. Cars will be parked 90% of the time and will be in driving mode only around one hour per day (Pasaoglu, *et al.*, 2013). To reflect this: · Ownership rate of 0.4 cars per capita · Cars drive 20 000 km per year · On average, 60% of the EV will be available, and grid connected	There will be a shift towards car sharing and autonomous vehicles and a decline in private vehicles. Cars will benefit from higher utilisation rates and hence reduce their idle time when they are available, and grid connected. To reflect this: · Ownership rate of 0.25 cars per capita · Cars drive 60 000 km per year · On average, 20% of the EV will be available, and grid connected

Figure 43: EV and grid usage when there is no innovation in mobility-as-a-service

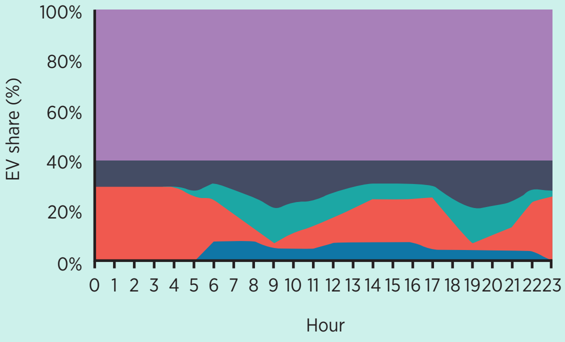
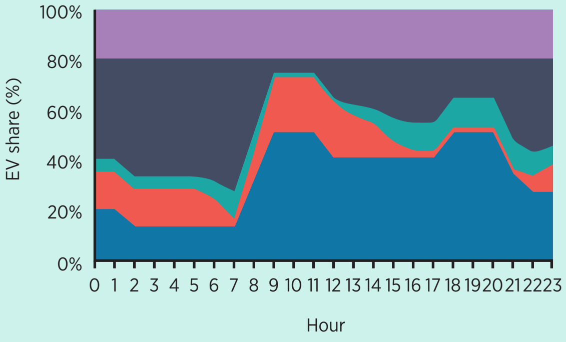


Figure 44: EV and grid usage in a mobility-as-a-service scenario



● EV batteries reserved for grid assistance ● Available and grid connected

● Cars not at home or at work (not connected) ● Cars driving ● Cars charging

Table 26: Implications of innovation in fully smart charging (V2G)

INNOVATION IN V2G	
NO	**YES**
The batteries of EVs cannot be connected to the grid to provide flexibility services, *i.e.*, to be charged to reduce curtailed renewable electricity, or to be discharged avoiding the dispatch of costlier marginal units and shaving peak load.	Part of the EV batteries is available to provide grid services. The size of the battery that is available and grid connected depends on the presence of MaaS in the system. To reflect this: · No MaaS: 60% of the EV battery is available · MaaS: 20% of the EV battery is available

Other assumptions that are used to model the presence of EV in the system in 2030 are presented in Table 27.

Table 27: EV-related assumptions (CEEME, 2017)

In 2030	
EV penetration in passenger car fleet	50%
Fuel economy	0.17 kWh/km
Battery size	80 kWh

Source: CEEME, 2017.

The modelling tool chosen for this purpose was PLEXOS. This commercially available software makes it possible to create a representation of the electricity system reflecting load profiles, current capacity mix by source (*i.e.*, installed capacity and technical and economic parameters), fuel prices and renewable profiles. EVs were modelled with an additional EV load profile and as a single-system battery to represent the total EV battery available for flexibility services to the grid. The software calculated the optimal capacity mix that minimises the total costs of the system and meets the demand at the 2030 horizon and the optimal dispatch by type of technology in hourly resolution. It also calculated system indicators such as regional electricity cost, available energy, generation and fuel offtake.

The outputs of the simulations were then assessed against a set of key performance indicators that made it possible to measure how V1G, V2G and MaaS contribute in the integration of EVs in high-renewable energy systems. The modelling exercise provides results for the year 2030. This is complemented by a qualitative view on how the key performance indicators could evolve and be interpreted in 2050.

Finally, to assess merely the adoption of the innovations in the system and its impact on the remaining key performance indicators (*e.g.*, curtailment, average yearly electricity cost), etc., a sensitivity considering the same capacity mix of a business-as-usual (BAU) scenario is simulated for the system with a high share of solar. For this purpose, the model is forced exogenously to maintain the capacity mix in 2030 at the same levels as the expansion previously calculated in the BAU scenario.

Modelled cases

The chosen geographies are isolated in the sense that are not connected to any national or bordering system; thus they need to meet their demand with their own generating sources. Also, no exports are considered to neighbouring systems, and the totality of the electricity produced within the systems is consumed on-site.

The high-solar isolated system reflects an equatorial location with a close to 24% solar share in power generation and one of the highest annual solar irradiances in the area. There is a high potential to install

PV in the system, both in terms of land availability for large-scale PV plants and in terms of integrated PV in building rooftops, façades or windows.

The high-wind isolated system reflects a region with a 40% wind share in the power generation mix. The geography benefits from important wind resources, although the land availability for wind plants could become a constraint for future capacity investments in the system.

Apart from meeting the definitions above, the concrete selection of the geographies for the two cases also has been based on the availability of data for the system modelling in the future horizon, mainly: long-term view on the future load demand, availability of solar and wind load profiles, projections of the technical specificities of the technologies (*e.g.*, CAPEX, OPEX, efficiencies, etc.) and a good representation of the actual electricity system in terms of existing generation assets.

To perform the modelling and technical simulation, the PLEXOS tool was chosen. PLEXOS is used to model the two described cases and to simulate them under four different scenarios in a given horizon. The results of the simulations will make it possible to assess the impact of key EV-related innovations that can influence renewable energy integration in the power grid.

Modelling in PLEXOS

PLEXOS is a power system simulation tool that can build integrated energy models. It uses linear and mixed integer programming, optimisation and stochastic techniques to solve long-term expansion and/or short-term unit commitment models. For this analysis, a model of the electricity system of the two cases was built. The models represent the current state of the system in terms of capacity mix, demand, renewable profiles and fuels.

The models are first simulated in a long-term capacity expansion and investment planning mode (long term). For this, the models consider the existing capacity installed in the systems and will calculate the optimal investment decisions that are needed to meet the demand in 2030 and that minimise the net present value of the total costs of the system over the planning horizon (Energy Exemplar, n.d.) – that is, to simultaneously solve a generation and transmission capacity expansion problem and a dispatch problem from a central planning, long-term perspective. The models can choose between the following technologies: combined-cycle gas turbine, open-cycle gas turbine, solar PV and wind. These technologies are modelled according to the economic and technical parameters of 2030.

Once the capacity mix required to meet the demand in 2030 is known, the models will be simulated under a unit commitment and economic dispatch mode (short term). This phase is chronological, hourly, and will better enable the analysis of the EVs on the system.

Table 28 summarises the list of key inputs used for the modelling and their sources.

In addition, the presence and integration of EV in the system is modelled in PLEXOS with two elements.

1. EV load (MWh): in the form of a profile, to represent the extra electricity demand that EVs will add to the system when connected to the grid for charging. The load profile will be influenced by the presence of smart charging technologies in the system, by future mobility trends and by the number of EVs on the roads.

2. EV battery (MW + MWh): to represent the flexibility services that EVs can provide to the grid when being discharged or charged. This is modelled as a single-system battery with a size of all the battery capacities of the EV that will be available for grid services in the future.

The EV load is added on top of the system load and is integrated in the demand-supply balance solved by PLEXOS. Also, the model chooses how to dispatch the EV batteries in an optimal way. How the model uses the EV batteries to balance the system will influence the impact that the EV will have on the grid and will be further observed in the key performance indicators.

When the simulation is completed, PLEXOS provides the optimal capacity investment decisions needed to balance the future load of 2030. At the same time, PLEXOS also provides the dispatch of the different technologies. Given this, the main outputs provided for 2030 are:

- Installed capacity by source (MW)
- Generation by source (MWh)
- Available energy by source (MWh)
- Fuel offtake by source (terajoule, TJ)
- Hourly marginal cost of electricity (EUR/MWh)
- Hourly dispatch
- Emissions (tonnes/CO_2).

Table 29 shows the resulting capacity mix for the BAU scenario after the expansion of the system, for both the solar isolated system and the wind isolated system.

Table 28: Input data list and sources required for the modelling

Current system infrastructure in 2017	
Generation capacity (MW) by source	CEEME, 2017
Load (MW) and yearly profile	CEEME, 2017
Fuel costs (EUR/GJ)	CEEME, 2017
Load profiles of wind and solar	CEEME, 2017
View in 2040	
Technology CAPEX and OPEX for future investments	CEEME, 2017
Load (MW) and yearly profile	CEEME, 2017
Fuel costs (EUR/GJ)	CEEME, 2017
Load profiles of wind and solar	CEEME, 2017

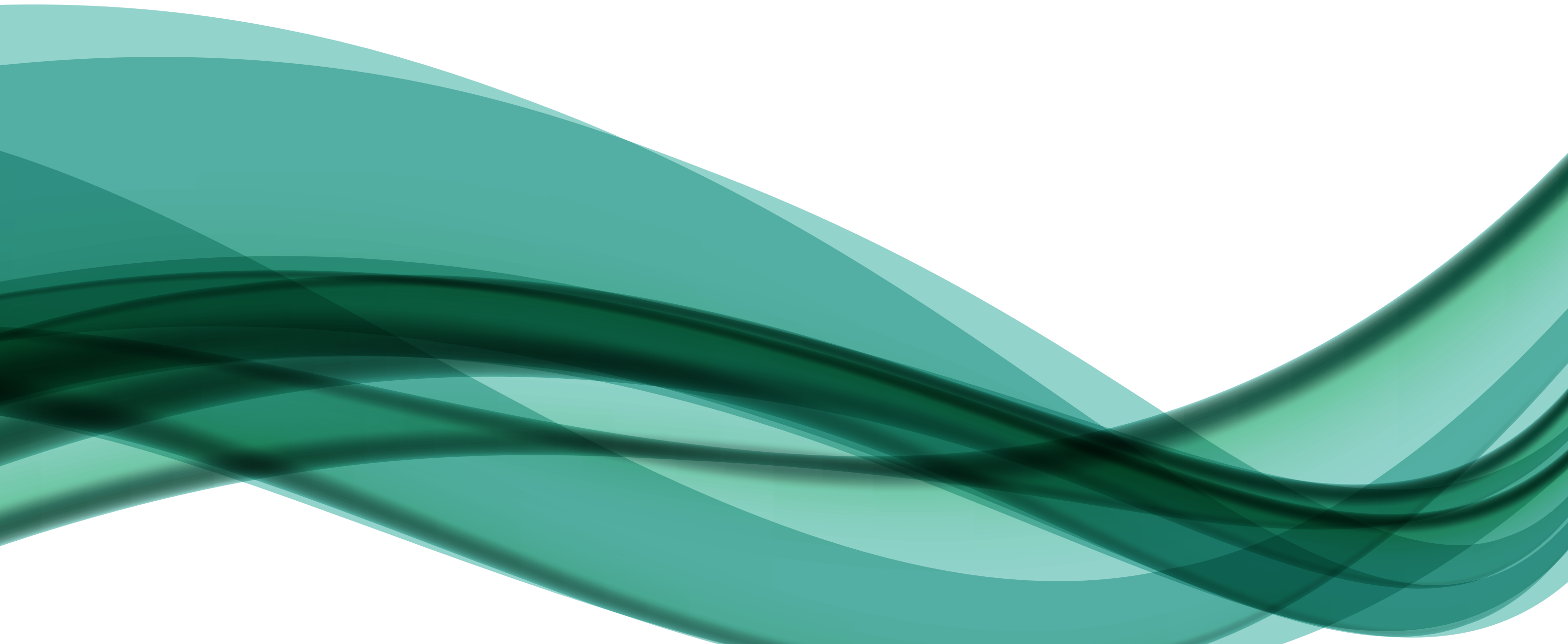
Table 29: Installed generation capacities in long-term BAU scenarios for both systems

Solar case 2030 BAU		**Wind case 2030 BAU**	
Category	**Installed Capacity (MW)**	**Category**	**Installed Capacity (MW)**
New CCGT	604	New CCGT	500
New solar	336.8	New OCGT	1 000
New wind	31.6	New solar	300
OCGT	238	New wind	1 800
Solar	109	CCGT	1 261.4
Wind	0.6	OCGT	31.5
Geothermal	5	Solar	680
Internal Combustion	606	Wind	297.5
Biomass	60.7	IC	4.26
Distributed solar	42	Biomass	64.1
		Distributed solar	329
		Combined heat and power	21.09

Examples of other studies: smart charging impact

Table 30: Examples of studies assessing the impact of EV charging strategies

REPORT	STUDIED POWER SYSTEM	SCENARIO	MAIN ISSUES AND KEY INDICATORS	FINDINGS
RMI, 2016	5 selected US states: California, Hawaii, Minnesota, New York, Texas	23% EV penetration in the fleet in 2030, i) uncontrolled charging mode, ii) optimised charging mode	Peak load increase with high EV penetration, which will increase the generation and distribution grid capacity	A big difference in peak load is found in the two scenarios. For example, in California: i) all EVs in uncontrolled charging mode would increase the peak load by 11.14%; ii) with smart charging, this would increase the peak load by only 1.33%. Smart charging can help optimise the grid resources and avoid having to invest in new peak generation capacity.
Taljegard, 2017	Denmark, Germany, Norway, Sweden	100% EV penetration in 2050, i) including electric road systems (ERS); ii) including ERS and V2G	EV charging correlates with the electricity system peak load and thereby increases the need for peak power capacity and an increase in CO_2 emissions	i) If no V2G is applied, the ERS would increase the peak of the net load curve by 20% in Scandinavia and Germany (from 127 GW to 152 GW); ii) If V2G is applied, passenger EVs will smoothen the net load curve in the Scandinavian and German electricity system so that the hour with maximum net load is reduced by 7% (from 127 GW to 118 GW).
McKenzie *et al.*, 2016	Island of Oahu, Hawaii, US	Over 130 000 EVs on Oahu by 2045, and 260 000 with US Energy Information Administration high oil price; 23% of electricity produced from renewables, very high solar and wind penetration following the Renewable Portfolio Standards	Given the island's mix of renewable resources, without EVs, 10% to 23% of combined solar and wind energy would need to be curtailed	With smart charging (*i.e.*, if EV charging perfectly tracked the solar and wind profiles), then up to a 18-45% reduction in renewable energy curtailment, depending on the charging behaviours and on the type of smart charging
Chen and Wu, 2018	Guanzhou region, China	Case based on real typical daily summer load curve in Guangzhou with 1 million EVs	EV charging correlates with the electricity system peak load and thereby increases the need for peak power capacity	One million EVs will increase the peak load of the grid by 15% without any charging control. However, the fluctuation will be reduced by 43% without V2G technology, while it can be reduced by 50% if V2G is available.



www.irena.org

www.facebook.com/irena.org

www.twitter.com/irena

www.instagram.com/irenaimages

IRENA
International Renewable Energy Agency