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Handbook on Planning and Operating an E-Mobility Infrastructure

dena

German Energy Agency

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Deutsche Energie-Agentur GmbH (dena)
German Energy Agency
Chausseestrasse 128 a
10115 Berlin, Germany
Tel: +49 (0)30 66 777-0
Fax: +49 (0)30 66 777-699
Email: info@dena.de
Internet: www.dena.de

Authors:
Karsten Burges, RE-xpertise
Thorsten Schlösser, Energynautics
Eckehard Tröster, Energynautics

Contributors:
Carsten Bamberg, dena
Lea-Valeska Giebel, dena
Jascha Lackner, dena
Katerina Simou, dena

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Executive summary

The growing momentum of transport electrification around the world translates into increased load on the distribution network through BEV charging.

The increase in load will affect the planning and operation of distribution networks, and the question arises of how the load can be managed cost-effectively without compromising security and supply quality. This handbook provides guidance on the measures to be taken by distribution system operators (DSOs) to stay ahead of the electric vehicle network integration challenge.

Higher peak loads from BEV charging must be accounted for in system planning.

The impact of individual BEVs on the network depends on the charging power, the duration and the time of day. Typically, charging electric vehicles during existing peak load hours is most critical. The impact of the BEV fleet depends on the number of BEVs being charged simultaneously within a given network area, otherwise known as the simultaneity factor. Simultaneity factors depend on country-specific elements and are calculated based on local monitoring data. DSOs use simultaneity factors to plan for sufficient capacity for BEV charging in newly built networks. Until sufficient monitoring data is collected, an update of planning routines should at least consider providing some spare capacity, e.g. selecting underground cables with a larger cross section in case of new installations.

Inflexible charging sessions follow conventional load connection routines already established at the DSO. Sessions may be inflexible due to the use case (fast charging along the motorway not tolerating any delay) or because the DSO cannot influence the charging process due to a lack of technical means or authority.

Managed charging makes it possible to integrate large BEV fleets into the distribution systems at minimum cost.

Fundamentally, the option to manage the charging process, for example, to avoid peak load hours, makes BEV charging flexible. Flexibility is usually available in cases where the vehicle stays longer at the charger than necessary for charging, e.g. at home, work or at the depot. In addition to managed charging, the following options can also be applied:

- **Time of use (ToU) tariffs**, where the electric vehicle driver is incentivised to charge during off-peak hours. ToU tariffs are preferred as a quick solution to reduce the load.
- **Local load management**, which ensures that electric vehicle charging combined with other loads is kept within the power limitations of the network connection point. This option is aimed more at buses.

While these alternatives help reduce peak load, they are no guarantee. Network planning must assume higher safety margins than those provided by managed charging.

Instruments for reducing peak loads must be integrated into DSO system operations.

When applying ToU tariffs for BEV charging, DSOs and energy suppliers may build on existing experience with residential ToU tariffs. At the same time, charging point operators (CPOs) and mobility service providers (MSPs) can introduce local load management to optimise their services against power prices or stay within contractual or physical ratings.

DSOs have to take the lead when integrating BEV charging into distribution networks. Managed charging and ToU tariffs require improved load flow monitoring in low voltage distribution networks. This may be implemented locally or integrated into the DSO's dispatch systems. Suitable commercial solutions supporting managed charging will be available in due time and will have to be aligned with the DSO's infrastructure and processes.

The regulatory framework should allow for flexible charging to integrate BEVs efficiently into the grid.

It is the DSO's responsibility to define a framework of technical rules and standards for network compliant electric vehicle charging. This framework should include basic requirements (safety of personnel, phase imbalances, power factor). Simultaneously, the DSO must inform policy about the advantages of influencing the charging process and deploying flexibility from a distribution system perspective. The DSO can also contribute to designing incentive schemes or mandatory provisions for managed charging. Finally, sufficient remuneration has to be secured to cover investments related to the integration of BEV charging into the distribution network.

Key DSO actions for network integration of EV charging

- **Update planning routines** for newly constructed network sections to include capacity for future EV charging.
- **Influence regulatory design** to allow DSOs to utilise EV charging flexibility and to steer charging station installation.
- **Increase network visibility** through mandatory charging station registration with the DSO and basic network monitoring.
- **Establish time-dependent electric vehicle charging tariffs** to incentivise charging during low load hours in case the DSO has pre-existing knowledge on time-of-use tariffs
- **Include a peak-load based price component** in the electricity cost to non-residential consumers to incentivise local load management.
- **Develop a managed charging roll-out strategy** based on current network capacity and expected electric vehicle charging load.

1 Introduction

The current status of e-mobility and its growth potential vary significantly among different countries. While countries like Norway, the Netherlands and Germany have already gained significant experience with growing e-mobility markets, other countries like Turkey, MENA countries and island states like the Dominican Republic are just starting to expand their electric vehicle fleets. Driven by climate policies, both groups of countries articulate high ambitions to grow this segment further. Hence, both groups would benefit equally from a straightforward overview of the challenges associated with integrating charging infrastructure for electric vehicles into the electricity grid. The aim of this document is to provide such an overview in an easily accessible manner.

Objectives

Electric vehicle charging significantly increases the load on electricity distribution networks while also contributing to energy consumption growth. Because of the expected dynamic or potentially disruptive growth of e-mobility, a strategic view and understanding of the implications it can have on distribution grids is a precondition for its sustainable progress. The existing distribution grids have never been designed for this application. Hence, concepts for planning and operating distribution grids must be revised and further developed. The purpose of this short analysis is to provide an overview of the main obstacles to the adequate planning and operation of an e-mobility infrastructure in existing and new distribution networks and how these obstacles can be overcome.

This document reflects the views of diverse stakeholder communities from the power industry, the mobility sector, policymakers, etc. One dedicated purpose of this overview is to facilitate further in-depth discussions between these communities. These discussions will benefit from concise and easily accessible guidance concerning infrastructural considerations of e-mobility in a handbook-like format. The document contributes to informing stakeholders on infrastructural e-mobility considerations and acts as a guideline. By applying the information, the responsible stakeholders will be able to reduce uncertainty in dealing with infrastructure planning and development for e-mobility and related regulations. In this way, this handbook will help them with short-term decision-making on this topic and help them prepare adequately for mid-term needs.

Approach

This short analysis will summarise the state of the art and ongoing e-mobility trends, covering vehicle technology, charging infrastructure and power system integration. The information is compiled based on a review of existing publications and results from research projects.[1] These sources have been screened, and the relevant outcomes have been extracted and refined. Interviews with international experts helped support and verify the conclusions presented here.

The analysis will address relevant questions as, by nature, there will be different views on the matter rather than simple answers. The ambition is to illustrate the spectrum of options and choices.

Scope

The analyses and assessments do not focus on a specific country or jurisdiction. This makes it possible to provide an unbiased review and evaluation of options. Dedicated attention will be given to international studies focusing on **countries whose power infrastructure is not yet substantially digitalised**.

Different technology options exist for decarbonising road transport. In addition to **battery electric vehicles (BEV)**, hydrogen-based fuel cell electric vehicles or electric road systems (e.g. catenaries) are also among the proposed options and are actively developed. However, this handbook focuses on integrating charging infrastructure into distribution grids. This restriction to BEV does not imply any judgement regarding the prospects and benefits of other technology options.

Plug-in hybrid electric vehicles (HEV) have been a significant segment of new registrations over the past decade. However, they do not promise deep decarbonisation (Plötz, Moll, Li, Bieker, & Mock, 2020); hence the proportion of HEV in the vehicle fleet will be limited in the long run. Additionally, their charging requirements and grid impacts are limited compared to full battery electric vehicles. For that reason, we do not address this technology option in detail.

[1] Dedicated modelling or analysis of primary datasets is beyond the scope of this handbook.

2 International context and trends

When discussing challenges related to charging infrastructure for e-mobility, there are different segments which should be considered, among others, privately owned passenger vehicles, public transport and long-haul trucks. Each segment has its specific operational requirements. The penetration of e-mobility differs per segment due to technology readiness and the ability to match the particular operational requirements. Different geographical regions, as well as policy and economic framework conditions, will influence the dynamics of e-mobility as well.

In this section, some of these aspects and interactions between those factors are very briefly described to provide a basis for the techno-economical assessment in the following sections.

2.1 Mobility segments in road transport

Undoubtedly, the decarbonisation of road transport is a major challenge. However, the specific challenges in terms of technology, power system integration, market organisation and regulation differ per segment and application. For that reason, any analysis must address them specifically. In this report, we introduce selected segments in road transport and distinguish them by some typical parameter ranges:[2]

Individual personal mobility:[3] The average daily mileage of private passenger vehicles is between 30 and 50 km, resulting in an annual mileage of 10,000 to 15,000 km. If the same vehicles are used for business purposes, their annual mileage is often higher, ranging from 15,000 to more than 50,000 km. The specific energy consumption of passenger BEVs ranges from 0.15 to 0.3 kWh/km.

Charging locations may be private, e.g. located at the vehicle owners' premises, semi-public or public. Sufficient public charging points are necessary for user satisfaction, even in the early stages of e-mobility. With a growing proportion of BEVs in the vehicle population, the need for public chargers scales more or less proportionally to the number of BEVs. A European Union proposal suggests at least 1 kW of publicly accessible charging capacity per BEV (European Commission, 2021).[4] Of course, this is only a rule of thumb that should not be generalised and applied to other regions without analysing the actual mobility patterns.

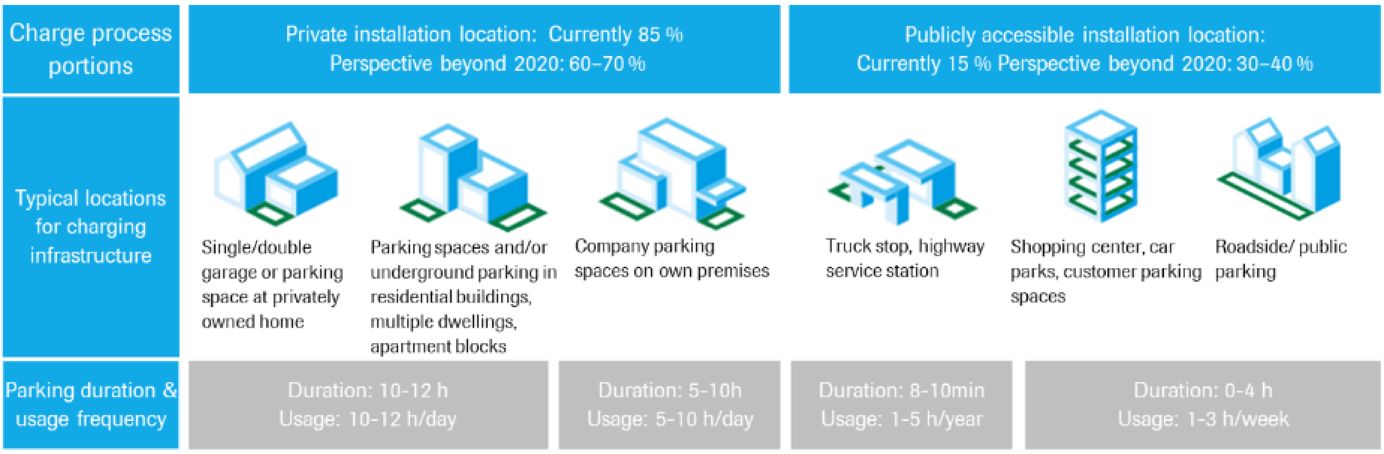

Figure 1: Typical locations for charging infrastructure, common usage patterns and shares (Germany). Source: (Verband der Automobilindustrie VDA, 2019)

[2] Parameters vary substantially within a country and even more between different geographical regions. With further technology progress, some of the parameters may also change over time. Nevertheless, these approximations help to illustrate the consequences of e-mobility on the power system.

[3] Some individual short-distance mobility can be covered by other carbon-free options like walking and cycling. Such options may be stimulated by policies. In addition, shifting from private vehicle usage to car sharing and carpooling promises emission reductions per person-km. A modal shift from individual vehicles to alternative options is crucial for the efficient decarbonisation of mobility. As the focus of this analysis is the integration of electric vehicles and their charging infrastructure into distribution networks, a modal shift and carbon-free forms of mobility are not addressed specifically in this assessment.

[4] Assuming 11 kW as a common value for charging capacity, this corresponds to the previously set ratio of one public charging point per 10 vehicles (European Commission, 2014).

Each of the following charging locations is associated with a typical charging pattern in terms of time and capacity (see Figure 1).

- **Residential charging:** BEVs used for individual mobility purposes are typically parked longest near residential buildings, either on private or public ground. The parking time (e.g. overnight) is usually substantially longer than the time necessary to recharge the electric vehicle battery, thus allowing for a flexible charging process.
- **Workplace charging:** The BEV is parked at the workplace during daytime working hours. The parking time is usually longer than the time necessary for recharging, which also allows for a flexible charging process.
- **Opportunity charging:** The BEV is parked while the driver performs various activities (e.g. shopping). This also includes short leisure activities, such as restaurant and cinema visits. These activities lasting up to 4 hours provide further recharging opportunities. In order to receive a sufficient recharge within the given time, fast charging is ideal. Flexibility for delaying the charging process is very limited.
- **Highway charging:** Includes all charging scenarios where the electric vehicle driver actively waits for the car to recharge to continue their journey. There is no flexibility, and the provided charging power is at least 50 kW.

Fleet owners/operators: Various fleets of light vehicles offer good preconditions for electrification (Linssen, Gillessen, Heinrichs, & Hennings, 2017). Examples are taxi companies, postal and other delivery services or healthcare companies providing at-home services. The various use cases require different types of vehicles and result in a diverse range of requirements. In some of the applications, it is possible to plan routes and charging times. Depot charging is predominant, but some public or semi-public opportunity charging may be required for unconstrained fleet operation.

- **Depot charging:** Occurs outside operational hours. Flexibility to delay charging processes is typically available and often already used by the depot manager to reduce peak power.
- **Opportunity charging:** Uses short breaks at selected locations. The charging process is not flexible.

Public transport:[5] Common daily mileage values for urban buses are between 150 and 300 km and may be higher for regional buses. The specific consumption is between 0.9 and 1.8 kWh/km (Grijalva & Lopez Martinez, 2019), depending on the design and type of the bus. Among other factors, depending on climate conditions, heating or cooling of the passenger compartment may significantly increase consumption. Depot charging may not be sufficient to support full-day operational cycles. In those cases, additional opportunity charging must be provided. Some options include chargers at the final destination and on route bus stops (Figure 2) or electric road systems on certain sections of the daily route (Figure 3).

Figure 2: Opportunity charging of an urban bus at its final destination. Source: (Arbeitsgruppe Innovative Antriebe Bus)

Figure 3: Opportunity charging of an urban bus using an electric road system on selected sections of the route (Source: (Harák, 2020))

Trucking sector and heavy-duty vehicles: Within this sector, diverse use cases exist, each with specific vehicle designs, operational regimes and technology choices for charging. Major application segments to be differentiated are:

- Regional distribution: Daily distances are typically between 200 and 500 km (Phadke, Khandekar, & Abhyankar, 2021). Depending on the truck size and design, a specific energy consumption between 1.0 and 1.5 kWh/km is realistic. Depot charging is dominant, supported by some destination charging

[5] In various cities, particularly in Eastern Europe, trolley busses with direct supply and no on-board storage have been and are still in operation. This technology is not considered here, as we are focusing on battery electric buses.

when loading and unloading goods. Opportunity charging along the motorway is an exception. However, vehicles may be operated in shifts with changing drivers, resulting in longer daily distances and less time available for depot charging.

- Long haul: Driving distances go up to 800 km per day, in some cases even further (Borlaug, et al., 2021). Tractor-trailer combinations are dominant. Specific energy consumption is expected to range from 1.3 to 1.5 kWh/km (Earl, et al., 2018), (Fulton & Burke, 2019) by 2030, assuming aerodynamic optimisation. For long-haul driving, depot and destination charging will be necessary in addition to opportunity charging along the motorway. In Europe, driving regimes are influenced by health and safety regulations. The obligatory resting times for the driver can be used for opportunity charging.
- Urban services and construction: The distances are limited, but power demand may be high. Other technologies will coexist with battery electric designs. Depending on the application, quite different ratings and charging solutions, e.g. battery swapping,[7] may be applied.

2.2 Trends and drivers in mobility sectors

<u>Individual mobility</u>: So far, the number of passenger vehicles per capita correlates with the GDP. In developing countries, this figure typically is lower than in highly industrialised countries (see Figure 4).

The population in many industrialised countries is stagnating, and vehicle markets are growing slowly or are saturated. To a large extent, new vehicle registrations concern replacements. After a decade, a large proportion of the fleet is replaced by new models.

The conditions are different in many developing countries. Without policy intervention, the vehicle per-capita numbers are likely to increase with further economic development. The population is typically going to grow as well. Hence, the vehicle stock tends to grow significantly in absolute numbers.

The lower per capita number of existing vehicles in developing countries might suggest an easier phase-out of internal combustion engines (ICE). However, the

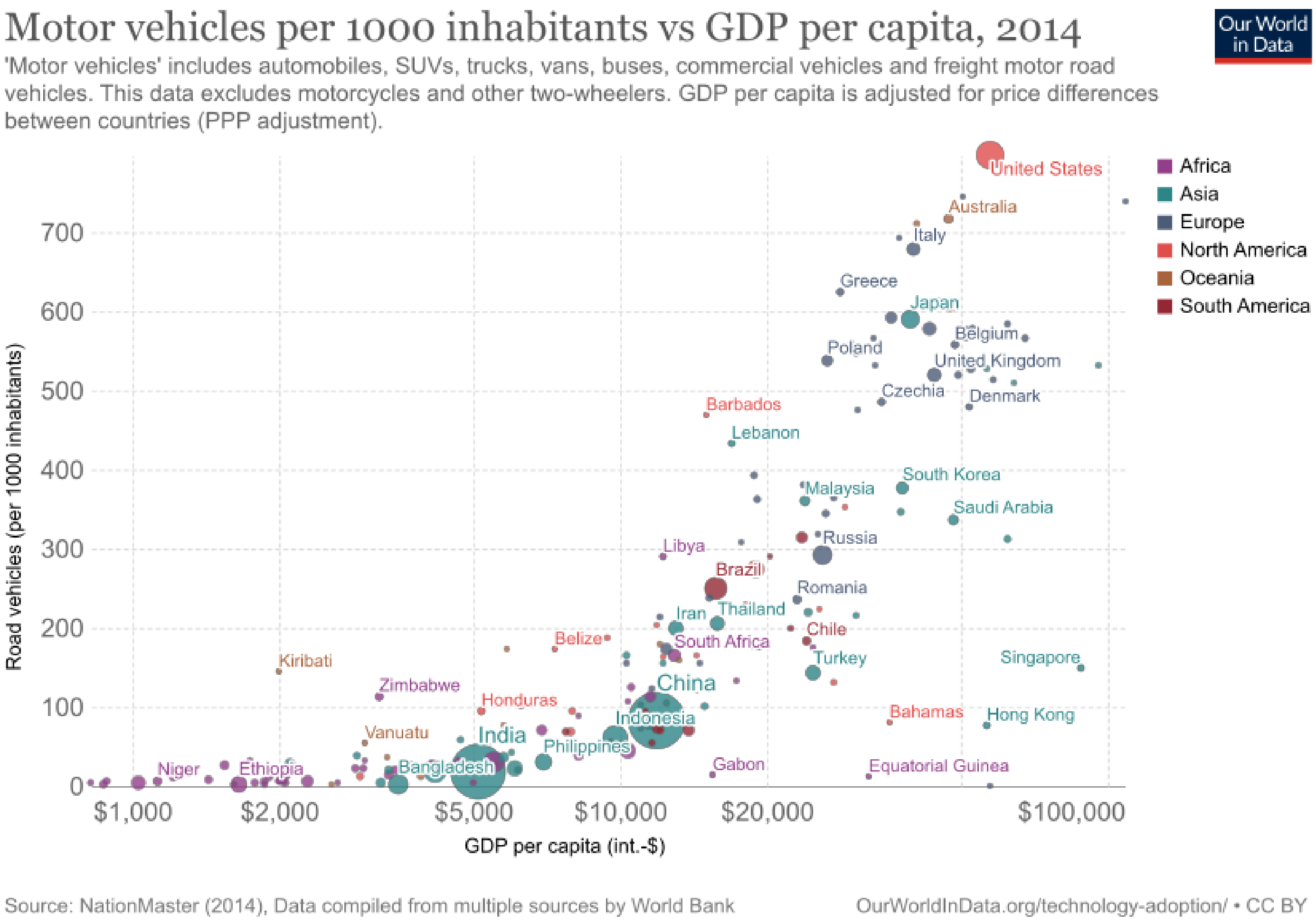

Figure 4: Motor vehicles per 1000 inhabitants vs GDP per capita[6] (2014). Source: (Our World in Data)

[6] GDP corrected for purchasing power parity. For specification of methodology, see source.

[7]https://www.chinatrucks.com/news/2020/0306/article_9192.html

technical lifespan of vehicles is often longer than 20 years. Moreover, e-mobility growth rates in growing vehicle markets must be higher than in stagnating replacement markets, or the absolute number of ICEVs will also keep increasing. Hence, ambitious e-mobility policies in developing countries imply some 'leap frogging'.

Public transport: Public transport regularly requires public funding and support and, for that reason, development very much depends on dedicated policies. The necessity to set up initial infrastructure may form an additional barrier to introducing e-mobility. It is possible to introduce e-mobility incrementally. Typically, direct policy intervention is required.

Trucking sector: For truck fleet operators, a precondition for shifting from ICEs to BEVs is that operational processes are not adversely affected by technology choices. The sector will only accept the new technology if the charging capacity is high enough for fast charging (megawatt range) and the geographic coverage in the service area is sufficient. Particularly in the case of long-haul trucks, further technology progress is required. The total cost of ownership (TCO) will be the key criterion when making investment decisions if the technology and infrastructure are available. Technology outlooks are optimistic that break-even points will be achieved before 2030 in the case of short-haul trucks and before 2035 for long-haul trucks (Earl, et al., 2018). Manufacturers are already introducing models for short-haul distribution.

2.3 Key learnings from electric vehicle trends

The electrification of the mobility sector will impact every type of vehicle. Distribution system operators (DSO) will face different integration challenges at different times.

From a DSO perspective, it is important to keep track of upcoming charging requirements within their distribution area based on the expected electric vehicle uptake.

With highway and opportunity charging, the parking duration is not longer than the period required for BEV charging. No flexibility is available to reduce the network load. For these charging use cases, DSOs can use established routines for integrating conventional loads into their network.

With residential, work and sometimes depot charging, parking times regularly exceed the period required for BEV charging. Assuming a supportive regulatory framework, DSOs can utilise the available flexibility to reduce the network load by participating in managed charging (see Chapters 4.2 and 4.3).

3 Regulatory environment and organisation of the power sector – preconditions for BEV charging

Electricity is a public good, and policy must create the framework for reliable, fair, sustainable and cost-effective access to electricity. Policymakers address these objectives when structuring stakeholder relationships within the power sector and the interfaces to society. Understanding these relationships is crucial when discussing new responsibilities and roles in e-mobility and its interfaces with the power sector.

3.1 The institutional structure of power systems

Over time, the power industry has been vertically integrated in every country, with generation, transmission, distribution and sales to final customers organised in a single company. These companies operated in geographical regions or the whole country.

In many jurisdictions, certainly in developing countries, this situation is still common. Often, there are close relationships between the power industry and the governmental authorities responsible for power supply. The interfaces between the business entities within the power company are invisible to external stakeholders. The design and operation of these interfaces are solely under the purview of the power company. Adjustments and the implementation of new processes are straightforward if the regulator authorises these changes. This regulatory authority ensures the interests of the final customers but also participates in power system planning and development.

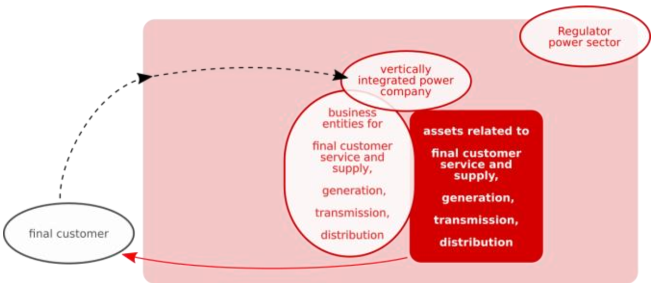

Figure 5: Simplified structure of a vertically integrated power sector. Red arcs = power flows; black dashed arcs = transactions at the interface. Graph source: authors

In contrast, in other jurisdictions like EU member states or in the US, power industries have been organised as liberalised markets with merchant actors in generation, trading and sales. The interfaces between these companies are explicit and organised as market platforms. Network companies (so-called natural monopolies) operate as a regulated industry under the control of a regulative authority. Their task is to guarantee the safe, secure and efficient supply of electricity and simultaneously support the fair and smooth operation of power markets. Regulatory interventions on merchant companies are minimised. The regulatory authority does not directly influence investment decisions, transactions or the structural organisation of these stakeholders.

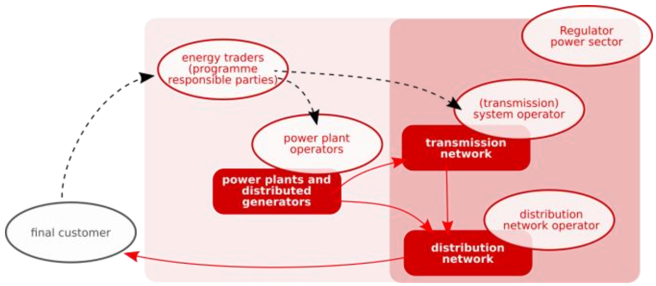

Figure 6: Simplified structure of an unbundled liberalised power sector. Red arcs = power flows; black dashed arcs = transactions at the interface. Graph source: authors

The structural differences influence the choices when designing the interface with the mobility sector.

3.2 Mapping of stakeholders and interfaces

With e-mobility, existing stakeholders are faced with new challenges, and new relationships between the power and transport sectors are created. This applies in particular to distribution system operators. Moreover, new roles and responsibilities emerge and must be assumed, either by existing stakeholders or by new entities. Similarly to the power sector, the mobility sector may be integrated or may be organised in a more liberalised manner with separate entities.

Figure 7 illustrates these new relationships. The stakeholders operating in the field of e-mobility are added on the left side of the diagram as ovals, their assets as boxes. Parts of this sector will be regulated as well. The institutional body of this regulator may or may not be identical to the one responsible for the power sector.

Ideally, the service is specified as charged energy. However, services related to charging time or charging events (session fee) can also be applied.

The CPO and the MSP may be a single company. However, in a liberalised setup, one MSP may offer their services via various CPOs, thus increasing their

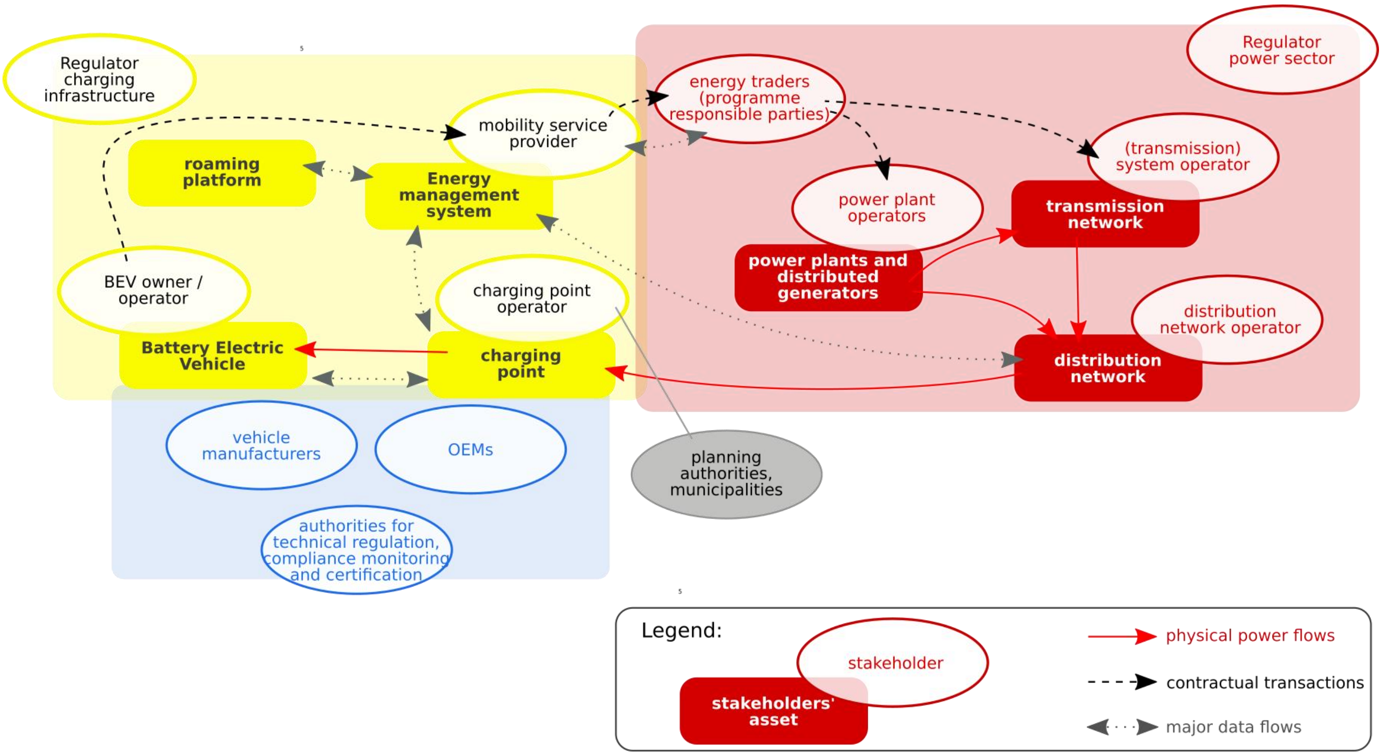

Figure 7: Stakeholders, relationships, transactions and flows related to e-mobility in a liberalised power sector (e.g. charger-centric approach). Graph source: authors

Key stakeholders in the mobility sector

The **charging point operator (CPO)** implements and operates charging points (CP), also called electric vehicle supply equipment (EVSE). These may be public, but it is also possible that the CPO takes care of operating semi-private or private charging points. Logically, the CPO takes care of communication and contractual negotiations with the DSO concerning grid connection and related construction works.

The **mobility service provider (MSP)** is the contractual party for the BEV owner/operator that offers and manages charging transactions. (A single, ad hoc transaction may be seen as a special short-term contract). This entity sells the service, buying the electricity from the power market. The MSP uses an energy management system (EMS) to optimise business operations. In the event of smart charging reflecting the situation of the distribution network, the EMS also has communication and control interfaces to the distribution network. At the current stage of development, communication links between the EMS and the DSO are exceptional and/or rudimentary.

geographical coverage without investing in hardware.

The charging point may be connected directly to the end user's network connection for at-home charging. In this case, no MSP is required.

BEV owners/operators use private or public charging points for charging their BEVs. Depending on the implemented functionality, the BEV owner may specify conditions for charging processes (e.g. next departure time, desired state of charge at departure). These conditions are communicated to the EMS and integrated into the MSP's overall service strategy.

BEV owners with private charging at their homes may combine charging with residential rooftop PV generation. In this case, a dedicated energy management system is often used to maximise direct usage of PV generation in the house and vehicle. This EMS does not communicate with the MSP or DSO; therefore, systemic optimisation is not supported.

A **roaming platform** collects and exchanges information regarding the transactions between MSPs and BEV owners/operators. Thus, BEV owners can charge their vehicles at an increased number of CPs with just one MSP contract. This platform processes the information and provides financial institutions with an interface (billing and payment). If there are several MSPs, independent roaming platform operators offer to streamline processes for their clients, charging a separate fee for their services (roaming).

If only one MSP exists, the roaming platform's functionality may be integrated into the MSP's assets.

Further stakeholders

In practice, the boundary between the power and e-mobility domains may be floating. Depending on the regulatory framework, the MSP and/or CPO may be closely linked to the power sector and be integrated into the business model of a vertically integrated power company. In this case, tasks and responsibilities within the mobility sector are (partly) allocated to entities within the power sector.

The following stakeholders are not directly involved in the operation of the BEV fleets. Nevertheless, it is of crucial importance that they be actively involved in the market development of e-mobility.

Vehicle manufacturers implement the communication interfaces between the charging infrastructure and the BEV user/operator based on international standards. Thus, they ensure that all the data required for managed charging is available. They may even take a key role in managed charging ('car-centric approach' – see section 4.2)

Charging point OEMs: As with BEVs, the required functionality for managed charging, communication and control must be implemented at the charging points. Compliance with international/industry standards is crucial for compatibility and safe charging.

Authorities for technical regulation, compliance monitoring and certification: Standards and interface specifications for BEVs and CPs are defined at the international level. Solutions and products may be manufactured locally or imported from other countries. To safeguard product compatibility, quality and safety, it is necessary to verify the compliance of industry solutions with international standards.

Planning authorities and municipalities: The spatial distribution of public charging points is an important aspect for user satisfaction and the commercial viability of the infrastructure. Space is limited, especially in urban areas, and charging infrastructure planning needs a strategic view, coordination and a careful balance of interests. Spatial planners need to be involved in an early stage of planning.

Key interfaces for the DSO

No matter which regulation is implemented, the immediate counterparts for the DSO are the CPO and the MSP. The CPO uses the physical connection to the DSO network, and the MSP is responsible for managing power flows. In the case of private charging, the network client – which is often also the BEV owner – may fulfil the role of CPO and MSP. While the physical connection (CPO part) is strongly related to network planning, applications and connection procedures (see Chapter 5), load flow management (MSP part) is strongly linked to network operation (see Chapter 6).

3.3 Policy intervention and instruments

Policy evaluation is not the scope of this report. However, in order to address the barriers related to the introduction of BEVs, some understanding of the key drivers is helpful. We distinguish policy instruments focusing on the economic and competitive position of e-mobility with respect to ICE from those addressing the required technical infrastructure. Reflecting the lessons learned over the past few years, this review is limited to individual mobility.

Incentives promoting the adoption of BEVs: Currently, the purchase prices of BEVs are still higher than those of ICE vehicles. Governmental incentives aim to improve the competitive position of BEVs. Common instruments are investment subsidies and tax deductions, as well as a combination of both. These instruments aim to reduce the gap in initial investment and/or operational costs. Weken analysed existing incentives and the resulting comparative position of BEVs and ICE vehicles in four European countries with substantial growth in EV markets (Harm Weken, 2021) (see Figure 8). The structure of the instruments and the market segments where they were applied have a huge impact on the benefitting sectors (private versus business BEVs). It is important to acknowledge that differences between instruments exist in different market segments even without e-mobility.

The different sets of instruments presented in Figure 8 effectively improve the competitive position of BEVs. Reduced taxes in countries like Norway and the Netherlands translated into high BEV shares in new registrations. In France and Germany, the tax burden for business vehicles is generally low; therefore, tax incentives show little effect. Here, BEVs must be further incentivised with subsidies.

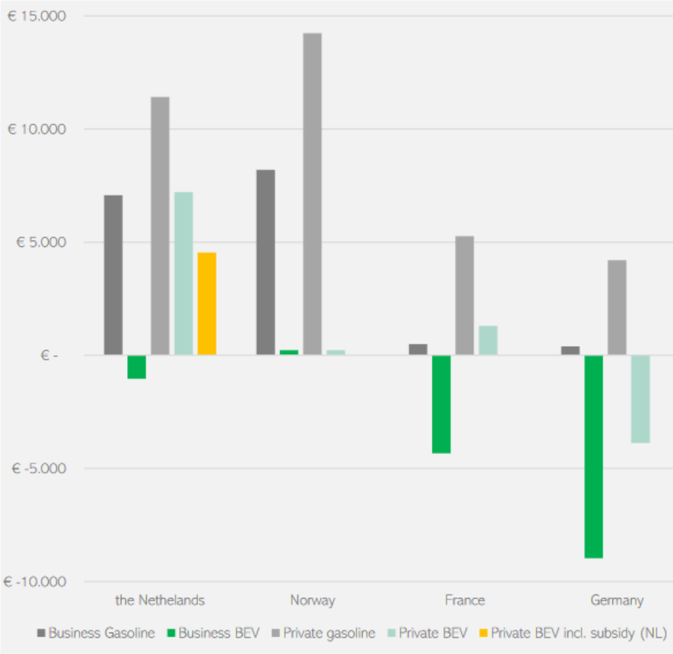

Figure 8: Average tax burden including incentives for different market segments of individual mobility in the Netherlands, Norway, France and Germany.[8] Source: (Harm Weken, 2021)

Incentives promoting infrastructure development

Adequate charging infrastructure is a precondition for taking up e-mobility. Social research consistently revealed that one of the most significant reservations of users is the fear of being exposed to mobility range limitations (range anxiety) and lacking charging opportunities (Deutsche Welle, 2021) (Continental, 2021).

Public and semi-public charging (e.g. at work or shopping centres) is important, even for users with access to their own residential charging facilities. In an early stage of development, the necessary investments will not be placed in a completely merchant approach; therefore, policy intervention is required.

Fixed investment subsidies for charging points [(KfW) – expired], [(GOV.UK, 2021) - to expire partly in March 2022] and tendering procedures where the resulting support for a set of charging points is found in a competitive procedure (Federal Ministry for Digital and Transport, 2021) are some of the incentives being applied. Normative approaches are applied as well. Several European regions introduced an obligation to offer BEV charging options in newly developed or renovated building projects with their own parking facilities [(REUTERS, 2021) UK], [(The Brussels Times, 2021) Flanders, Belgium] [(Appunn, 2021) Germany].

Framework and incentives for smart charging

The crucial importance of smart charging will be discussed in more detail in Chapters 4.2 and 5.4. The fundamental question is which mechanisms can be used to encourage users to participate in smart charging schemes. An obvious instrument is flexible tariffs incentivising the efficient use of the power system and balancing these aspects with end users' needs.

The flexibility potential of EV charging processes and their scale is new for power system and network operators. In most countries, existing tariff structures do not anticipate these use cases. In all jurisdictions, parts of the tariffing schemes are regulated, i.e. they cannot be changed by the power industry without the approval of the regulating authorities and the appropriate legal framework implemented by the government.

Changing tariff structures has potentially many side effects, and the implementation of changes takes time due to its complexity. Regular adjustments will be prepared as e-mobility grows. Measures must be balanced carefully.

Due to these challenges, it is important to start reviewing and amending tariff structures for charging and the underlying regulation in an early stage of development (see Chapter 6.2).

3.4 Regulatory design

The regulatory design to include BEV charging in the existing policy framework depends to a great extent on the institutional structure of the power system. Unbundled power systems usually establish unbundled regulation as well: power system network, market and user requirements are defined as separate domains. In vertically integrated systems, the different requirements are often integrated and issued by one controlling entity.

It is preferable that regulations relating to BEV charging be aligned with already existing regulations for other provisions, such as the integration of photovoltaic systems into the distribution network.

A comprehensive set of regulations would cover the following aspects (see infobox).

[8] Methodology as defined in (Harm Weken, 2021): The average tax burden is calculated by adding all taxes to be paid over four years together. This includes VAT, purchase taxes and road taxes and subtracting purchase subsidies. The average is calculated for the B, C and D segments.

ASPECTS TO BE COVERED BY THE REGULATION OF BEV MARKETS

General provisions
- Purpose and scope of the regulation
- Definitions used in the document
- Referenced standards

Technical requirements
- Personnel safety aspects
- Network safety aspects
- Use of onsite renewable energy

Approval process for charging stations
- Need for a licensed installer
- Equipment certification
- Calibration of the meters
- Registration of the charging station
- The right to check conformity

Optional requirements
- Setting of plug types
- Market monitoring
- Customer payment methods
- Roaming
- Resale of electricity
- Charging tariffs

Final provisions
- Claims management
- Sanctions
- Retrofitting
- Entry into force

With their technical expertise, DSOs actively contribute to policy design to ensure that the regulatory framework reflects the necessary provisions for the safe and secure supply of electricity to BEV charging as well as other connected customers.

The infobox lists a number of optional requirements for BEV charging. The regulating entity often establishes rules on aspects not strictly related to power system security that improve the BEV users' experience.

For instance, in the Dominican Republic, an electric vehicle charging regulation is currently being developed. The regulating entity wants to set several additional requirements. All public charging stations must use certain plug types, or they will not be granted network access. In most other power systems, this decision is left to the market.[9] Furthermore, public CPOs in the Dominican Republic must monitor the electric vehicle market and adapt the plug types accordingly. Additionally, the payment method and the need for at least one roaming connection are defined within the regulation for ease of use by the electric vehicle driver.

Whether or not these additions make sense in other countries and are supported by the market will have to be evaluated on a case-by-case basis. The main advantage is that governmental bodies have more control over charging station development. However, there is a risk that charging station operators will not invest in this heavily regulated environment. Additionally, these requirements should be regularly checked to avoid outdated infrastructure.

Another key issue is that the resale of electricity is forbidden due to legal reasons. India, Bangladesh, the Dominican Republic and other countries in a similar situation have therefore defined electric vehicle charging as a service and not as the resale of electricity. This exemption makes it possible to bill the energy or power from a charging session without restructuring the energy law. BEV charging tariffs are set by the energy and electricity network provider. However, the charge point operator and other stakeholders can add additional surcharges to the tariff, thus creating a competitive environment. This applies similarly in Germany: the final electricity customer is the CPO. The electricity is then forwarded to a BEV that is not currently formally part of the power system.

Regulations addressing BEV charging cover more than network integration aspects. DSOs should be aware of the complete regulatory landscape since it has at least an indirect impact on network operation. For instance, if specific plug types are mandatory, it will most likely be the responsibility of the network operator to verify compliance when network access is granted.

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[9] Financial incentives require a certain plug type in other countries as well (e.g. in Germany).

3.5 Key learnings on regulation and organisation

DSOs define their rules and procedures for their clients. Simultaneously, they are subject to regulations and must comply with the legal framework. The DSO's ability to directly influence policy design is often limited. Nevertheless, observing and commenting on BEV-related policies is crucial for developing a consistent framework. Key questions that should be answered are:

- Who is responsible for the regulatory design? What are the regular communication formats between the DSO and the regulatory authorities? Are these formats sufficient for addressing strategic questions?
- How can the DSO itself contribute to the development of adequate regulations? Are there industry consultations or stakeholder dialogues? If not initiated by the regulatory authorities, can the DSO take action to develop shared views on adequate rules, procedures and economic framework conditions?
- What are the crucial regulatory aspects affecting the DSO's operation, as discussed in more detail in the following chapters? Do regulations related to BEVs address:
    - technical codes and standards;
    - application and connection procedures;
    - network development and/or operation;
    - network charges, tariffs and fees related to the DSO's business?
- Which of the aspects in existing or proposed BEV-related regulations are clearly critical from a DSO's perspective and need to be addressed in direct communication with the authorities?

Usually, it takes a long time to develop and implement regulations, often several years. Even if BEV penetration is currently low, DSOs must anticipate future needs. The risks related to late engagement are:

- At a certain moment in time, corrective measures related to procedures or technical codes are required. These may also apply to the existing stock of assets and result in a need to retrofit equipment, even on the client side.
- Outdated privileges or favourable contractual conditions may be difficult to change. Depending on growth rates, they may have been granted to many customers. If more stringent rules are going to be introduced, new clients easily experience this as discrimination.

4 Power system and charging infrastructure

Electric vehicle charging has a great impact on power systems. An early understanding of the upcoming challenges will help to adjust network planning and operational procedures accordingly. Suitable strategies, such as managed charging, are necessary to keep total power system costs to a minimum.

4.1 Generation, transmission and distribution face different challenges

Networks
Private and public charging points for BEVs are regularly connected to low voltage (LV) networks. Charging hubs and depots (buses, logistic hubs) may be connected to medium voltage (MV) distribution networks. Exceptionally large charging hubs may require a direct connection to high voltage (HV) networks. Examples are high power charging stations for BEVs and BE trucks on traffic-intense motorways or at logistic hubs.

Compared to previously existing loads in LV networks, BEV charging occupies a high capacity over relatively long periods. Increasing BEV penetration will impact the *planning* of LV distribution networks and their *operation*. To a great extent, this impact will be local.

The barriers to responding to e-mobility challenges in LV network *operation* are significant. There is little monitoring and control equipment installed in LV distribution. The roll-out of a 'smart-grid' infrastructure will take time, and the associated up-front investments are substantial.

This is different at higher network levels. In MV and to an even greater extent in HV networks, power flows and the operational status of network assets are permanently monitored. In regions with strong distributed generation growth, network operators not only invest in monitoring equipment but also regularly invest in network reinforcement and extension. In those regions, the additional load flows related to BEV charging can often be accommodated by the HV and transmission networks without further reinforcements.

Generation
BEV charging increases the system load and changes the existing load profiles. Depending on the combination of load profiles, the system peak load may or may not increase significantly. The growth of (peak) load must be reflected in the *planning* of the generation plant. Unit commitment and the *operational* dispatch of generation plants must be adjusted to the change in load profiles. Forecasting the aggregated load from BEV charging will be easier than predicting the generation of variable renewables. Due to the large number of units, aggregated patterns will be quite regular, and gradients will be manageable, at least as long as no external synchronisation occurs.[10]

The overall conclusion: the lower the power system level, the more pronounced the impact of BEV charging.

4.2 Managed charging affects both system planning and operation

A key proposition of integrating BEV charging into power systems is the associated inherent flexibility. In many applications, the charging of batteries may be scheduled within a certain interval without comfort loss for the user.

[10] One example of potential external synchronisation is the transfer of low market prices to end users: all BEV owners will tend to charge their batteries during those periods. Another synchronising situation is re-energisation after a blackout. Since BEV owners have waited some time to charge their vehicles, they will all reconnect at once. Such situations need to be avoided or at least carefully managed.

FLEXIBILITY OF BEV CHARGING – THE BASIS FOR CHARGING MANAGEMENT

Typical driving cycles of a private BEV cover an average distance of 30 km to 40 km per day. Even small vehicle models with a battery capacity of just 50 kWh offer a range of about 200 km per fully charged battery. Recharging this amount of energy once or twice per week is sufficient for unrestricted mobility.

A charger rated at 11 kW makes it possible to completely recharge the 50 kWh battery within 5 hours, twice a week or more frequently for less time. With these conditions in mind, choosing the moments, duration and charging power can take more aspects into account than the owner's mobility patterns – with no adverse effects on the user's experience.

The flexibility in timing and power offers the possibility to optimise BEV charging. From the power system perspective, managed charging may focus on the areas discussed previously.

- Optimise unit commitment and operational dispatch of the **generation** portfolio (for example, to increase the share of renewable energy in the generation mix);
- Facilitate the efficient operation of **power markets** (for example, help to reduce peak power prices);
- Support the efficient operation of **transmission** systems;
- Support the efficient operation of **distribution** systems.

These are partly contradicting objectives, each in the interest of different stakeholders. Hence, the starting point for the conceptual design of managed charging is a clear definition of objectives and balancing particular stakeholder interests. From a societal perspective, this implies policy choices.

Managed charging influences the charging profiles of individual users on a day-by-day basis – the relevance for system *operation* is obvious. But how does managed charging influence system *planning*?

The design case for (LV) distribution networks is the expected peak load (see explanation of Figure 12). This determines the rating of network assets, such as cables, transformers or protection devices. Overloading these assets beyond their design ratings cannot be tolerated because overloading reduces the technical life of the assets or can even lead to catastrophic failure.

Customer load is stochastic, and traditionally, peak load is estimated based on experience. This implies substantial safety margins. With the recent progress of smart grid concepts, the peak load of distribution feeders and transformers can be assessed by monitoring. However, the technical life of these network assets covers decades. During such long periods, the load is likely to grow further. For that reason, some margin in ratings will always be necessary.

For the network operator, managed charging offers a tool to **reliably** limit peak load. If necessary, the limitation can be enforced. This makes it possible to set the limited value as a reference when rating network assets. Appropriate ratings depend on the existing network loading, load profiles (see Chapter 5.4), the expected growth of (charging) loads and the acceptable managed charging interventions. Because of the long life of network assets, these aspects need to be assessed strategically.

WHAT IS THE BEV USERS' MOTIVATION TO PARTICIPATE IN MANAGED CHARGING?

The obvious motivation for BEV users to participate in managed charging are economic considerations:

- With common power market designs, generation is the only flexible and unregulated component in electricity prices.
- A potential drawback of wholesale power markets is the synchronisation effect: all users seeing the same incentives may have adverse consequences at the local level.
- Flexible components in network charges may be an option. This requires that the monitoring and communication infrastructure in distribution networks be connected to trading platforms.

More regulatory approaches:

- Managed charging is obligatory for all public charging and private charging with a Wallbox (Mode 3).
- Capacity is capped for charging without managed charging.

System planning includes designing and implementing the required communication and control infrastructure. Design decisions depend on the organisation and the technical approaches of BEV charging. Different entities are responsible for different parts of those infrastructures. Design conventions and technology implementation have to be aligned among stakeholders. These aspects will be discussed more in detail in Chapter 5.5.

4.3 Objectives and approaches to managed charging

Managed charging is an optimisation process between several interest groups. The aim is to optimise a specific charging session towards optimal stakeholder satisfaction at minimum cost. The most notable interest groups are:

- Network and system operators
- Electric vehicle users
- Energy provider
- Mobility provider

Network operators are responsible for ensuring the stability and quality of supply at minimum cost. This includes the prevention of network congestion (network operator) and frequency control (system operator). Electric vehicle users require a sufficiently charged vehicle without loss of comfort at the lowest possible cost. Energy providers want to optimise demand to match low-cost generation profiles. Lastly, mobility providers aim to increase the utilisation of the installed charging infrastructure.

These stakeholder interests do not always align. Mobility providers and BEV users might prefer direct full power EV charging, whereas network operators and energy providers might favour delaying the charging process. BEV charging at times of low energy prices could cause network constraints by synchronising the charging of a large number of vehicles.

While balancing stakeholders' interests, maintaining network stability deserves the highest priority. If the security and quality of supply are compromised, the charging process, as well as many other consumers connected to the same network, will also be adversely affected.

4.4 Vehicle-to-Grid – a special use case for managed charging

Vehicle-to-Grid[11] (V2G), also called bidirectional charging, allows reverse power flows in addition to a reduction in charging power. Suggested applications are short-term frequency control, energy arbitrage and the increased use of renewable energy (Schlund, 2021). Another use case discussed is, for example, the reduction of evening peak load caused by air conditioning: excess PV generation during the midday hours can be buffered in BEV batteries. Similar matches with other fluctuating loads, like heat pumps, are also suggested (Thormann & Kienberger, 2020) (Arnaudo, Topel, & Laumert, 2020).

Proposed use cases are typically driven by system-level objectives (*generation* and *transmission*). This implies the risk of not considering local network bottlenecks in the *distribution* system. Inadequate network design and protections may result in synchronised V2G overloading, tripping protections and leading to power loss in certain LV network sections. Uncoordinated V2G activities combined with distributed electricity generation further increase the risks. Dedicated monitoring, communication and control are preconditions for integrating V2G into distribution networks.

Compared to managed charging, V2G does not offer added value for mitigating local network congestion. Using unidirectional managed charging to reduce the charging load when needed, i.e. without reverse power flow, effectively avoids any overloading.

From a network *planning* perspective, V2G will never allow underrating the local assets with respect to other (new) loads, such as heat pumps, simply because the vehicles may not be available when the relevant situation occurs.

4.5 Key learnings – fundamentals of managed charging

Managed charging is the most cost-effective solution for integrating BEV charging into distribution networks. In the case of Germany, compared to unmanaged charging, managed charging makes it possible to reduce peak capacity without loss of comfort, reducing investments by 30% to 50% (Dorendorf, et al., 2019), (Navigant;, Kompetenzzentrum Elektromobilität; RE-xpertise, 2019). BEV sales will reach high levels soon, requiring managed charging. However, the real-world application of managed charging is still in an early phase.

It is the DSO's responsibility to develop a functioning monitoring system to ensure that all preconditions for managed charging are met.

The main responsibilities are:
1. Keep track of the current and expected number of electric vehicles and charging stations in the network area

[11] Other variants are Vehicle-to-Home, Vehicle-to-Building and Vehicle-to-Business. The objectives and implementations of these concepts differ substantially.

2. Monitor international managed charging approaches and their infrastructural needs
3. Review the suitability of existing regulations for electric vehicle charging
4. Influence policymakers to adopt policies in favour of managed charging

Monitoring electric vehicle deployment will ensure that internal processes are adjusted in time and will be ready once large quantities of electric vehicles need to be integrated into the network. The electric vehicle landscape will change drastically in electric vehicle forerunner countries within the next five years. Other countries will most likely follow shortly afterwards.

Commercial managed charging solutions will enter the market soon. DSOs should monitor progress in this field. If smart metering infrastructure is planned or already operational in the DSO's network, the possibility of integrating managed charging solutions with existing infrastructure should be checked to save costs.

A further task is to review existing regulations for their suitability vis-à-vis managed charging. Critical aspects include the reimbursement of DSOs and incentives for electric vehicle users to apply managed charging.

In most countries, even those with a significant BEV stock, the current regulatory framework does not support managed charging. DSOs have a vested interest in influencing policy to create an advantageous framework. Policy design and implementation take time and therefore need to start as soon as possible.

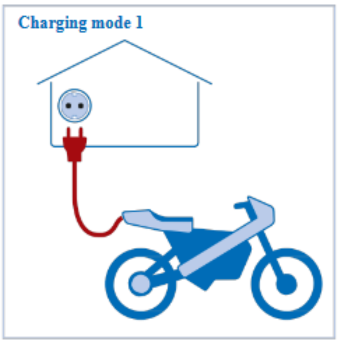
5 Distribution system planning

Distribution system planning requires knowledge of the expected grid impact of the various BEV charging use cases. This knowledge makes it possible to develop mitigation strategies that support efficient network design as well as safe and reliable operation.

5.1 Charging modes[12]

The international standard IEC 61851 distinguishes four charging modes. Their technical capabilities and their impact on the network differ.

Mode 1



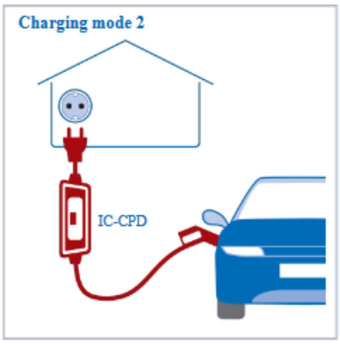
In mode 1, charging relies on a standard LV AC (230 V) wall socket. This mode is used mostly for charging at home. There is no communication between the electricity network and the vehicle. This can entail some safety risks; hence, charging power is restricted to 2.3 kW (230 V single-phase, 10 Amps, see IEC 61851-1) for small EVs only.

Mode 1 is of minor importance and has a marginal impact on network planning due to the energy requirements of the EVs allowed to connect (e.g. e-bikes and scooters).

From a DSO's perspective, there is no reason to be too concerned about mode 1 charging due to the low power levels. A potential exception would be countries where many light combustion engine vehicles (e.g. scooters) are already on the road, such as Vietnam and other Asian countries.

Mode 2

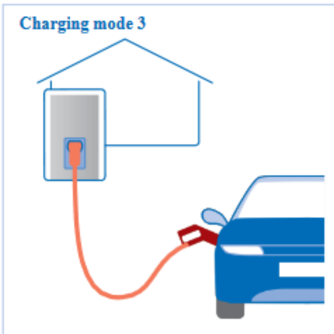
Mode 2 also uses a standard 230 V AC single-phase wall socket similar to mode 1. Additionally, the charging cable is equipped with a controller (ICCB: In-Cable Control Box). The ICCB controls the charging process and provides basic safety functionalities. As in mode 1, a standard charging capacity rate is 2.3 kW (230 V single-phase, 10 A). In principle, capacity values of 7.4 kW (230 V single-phase, 32 A) or 22 kW (230 V three-phase, 32 A) are possible.



Mode 2 is invisible to network operators and has not been reflected in network planning. Hence, mode 2 charging requires attention since the adequacy of the supplying network has not been checked. Even though it is unlikely that charging a single EV with this mode would create problems, a wider-scale roll-out can cause network issues (asset overloading in LV, imbalances, etc.). Most electric cars are shipped with a mode 2 charger. For the EV user, there is apparently no barrier to using this option. With inadequate framework conditions, there can be unintended incentives to avoid the installation costs of a mode 3 charger or to prefer (subsidised) household electricity tariffs over tariffs at public charging stations.

DSOs should therefore try to discourage mode 2 charging. However, the options are rather limited.

Mode 3



In mode 3, charging relies on a dedicated AC charger installed at a fixed location. With sound procedures implemented at the time of installation, the underlying electrical grid is checked to ensure safe operation. Mode 3 offers extensive safety features and optional managed charging and billing capabilities. Mode 3 charging points are typically rated for 11 kW or 22 kW charging with a three-phase grid connection.

Mode 3 chargers have higher ratings than, for example, common residential connections. The impact on existing LV networks may be significant compared to typical LV appliances. For that reason, the connection of mode 3

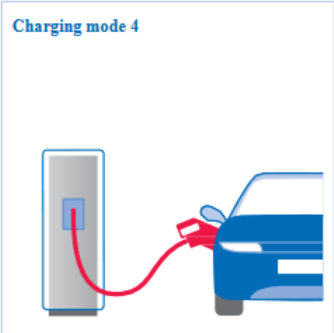
[12] The source of the figures illustrating the charging modes is (DKE in VDE, bdew, ZVEH, ZVEI, VDE FNN, 2020).

chargers requires an application process and the involvement of network planners.

DSOs have a vested interest in promoting mode 3 charging as the default option. Possible approaches include information campaigns and attractive pricing.

Mode 4

Mode 4 offers charging via dedicated DC chargers with power electronic converters integrated into the charging station that is installed at a fixed location. Mode 4 is mostly used for public fast charging, currently up to 350 kW.



Mode 4 fast chargers are typically installed on the MV or LV network, where the impact is accounted for prior to their installation. For low power applications, the individual impact is similar to mode 3 charging.

Ideally, DSOs develop public mode 4 charging infrastructure strategically together with transport authorities. One possibility is the development of regional heat maps linking highly frequented traffic locations with available network capacity. Logically, this is done in a collaborative effort between the distribution network and potential charge point operators.

5.2 Charging connectors

Plugs for electric cars have been standardised internationally with regional or country-specific differences. More powerful standards for electric truck and bus charging are expected in the future.

For AC charging (modes 2 & 3), IEC 62196 type 1 and 2 connectors are the universal standards relying on powerline communication (Figure 9). Type 1 is a single-phase charge plug and is mostly used in North America and Japan. Type 2 is capable of three-phase charging and is predominant in the rest of the world. For DC charging (mode 4), type 1 and 2 plugs are extended by two DC connectors and, as such, are called combined charging system 1 and 2 (CCS 1/2). CCS charging is possible with up to 400 A and 1000 V. CCS does not yet support bi-directional charging. Compatibility with bi-directional charging will be addressed in the ISO 15118-20 standard.

Tesla applies its own DC charging standard in North America. Recently, the company announced the development of adapters that will allow CCS BEVs to be connected, in addition to trials to open their proprietary charging network, which might result in the discontinuation of the Tesla standard in the future.

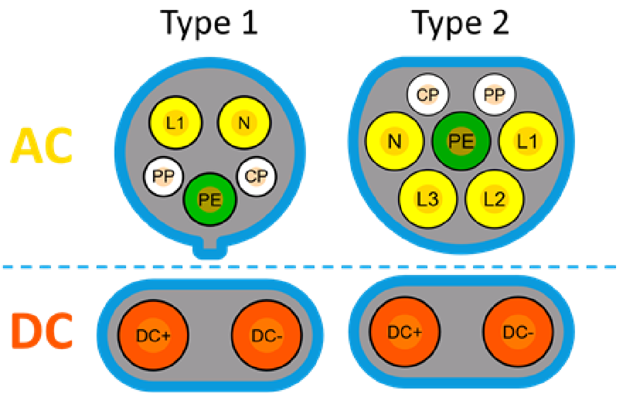


Figure 10: IEC 62196 type 1 and 2 plugs for AC and DC charging. Source: [(Charging Station, n.d.)]

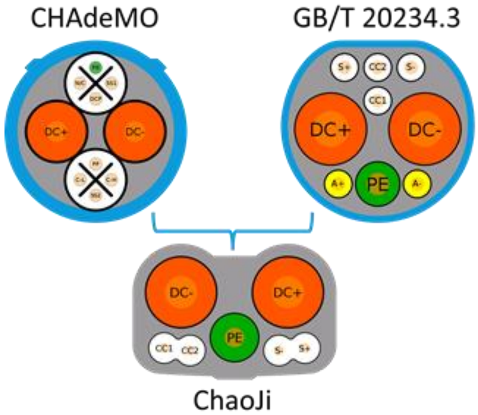


Figure 9: Japanese CHAdeMO and Chinese GB/T 20234.4 DC charging standards and their combined successor ChaoJi. Source [(Charging Station, n.d.)]

From a DSO's perspective, there is no network-related technical difference between the different charging connectors; therefore, there is no need to advocate for a specific choice. Aspects such as geographical context, market structures, dominating suppliers and national industry policy will dictate the connector type. Examples of practical considerations include:

- Travel to neighbouring countries should be comfortably possible.
- People living in Europe regularly visit their families in MENA countries, travelling by car. Matching standards, again, are convenient.
- Consistent, multi-national markets in one region make it possible to deploy economies of scale. Choosing an exotic standard will result in higher costs for end users.

5.3 Communication infrastructure

Chapter 3.2 introduced the necessity of stakeholder interaction to provide EV charging services. Several international communication standards exist for this purpose. In some cases, different standards offer the same functionality; in other cases, different standards offer overlapping functionality. Development is still ongoing and is likely to affect future communication interactions.

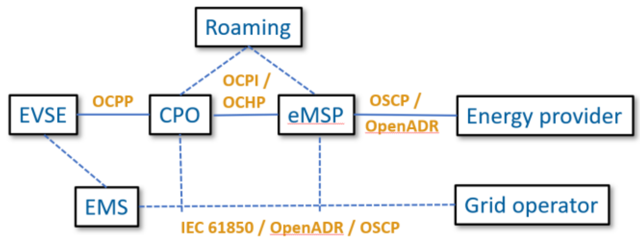


Figure 11: Standard communication interactions for EV charging.

Figure 11 shows the interaction and competition of the currently most important standards to connect the various EV charging interest groups. The electric vehicle supply equipment (EVSE), also called the charging station, is connected to the charge point operator (CPO) and potentially a local energy management system (EMS). The EMS is usually installed to optimise local energy consumption, for instance, by delaying the charging process until self-produced solar energy is available. The charge point operator is connected to the e-mobility Service Provider (eMSP) through either a direct peer to peer connection or roaming. Lastly, the energy provider and grid (network) operator interact with the eMSP or EMS to optimise the charging session according to their requirements. A description of the standards' core functionality is provided in the infobox.

From a DSO perspective, the EEBUS, ISO 61850 and OpenADR standards are most relevant for communicating network overloading directly to the CP or CPO.

The adopted standard depends on the DSO's existing communication infrastructure and the standards used in commercially available managed charging solutions at the time of installation.

The level of integration with the DSO's communication infrastructure depends on the chosen managed charging strategy (see Chapter 5.5). In principle, it is also possible to adopt DSO proprietary standards, but that will require managed charging solutions to be adjusted, thus increasing cost.

It is beneficial for the DSO to understand the principles of the other standards connecting the different stakeholders introduced in Chapter 3.2, although no detailed knowledge is needed.

COMMUNICATION STANDARDS FOR EV CHARGING

The open charge point protocol was first published in 2009. It is the de facto standard for charging station management by the CPO, such as billing, maintenance and charging power adjustments.

The EEBus standard is used for demand and generation management of distributed resources, including e-mobility.

OpenADR is mostly used in North America. It provides a standardised way to send demand response signals to small distributed resources.

ISO 61850 is widely used throughout Europe for substation control and monitoring, including EV management.

The Open Smart Charging Protocol was originally designed for EV smart charging but can integrate other resources as well, although it is not yet widely used.

The Open Charge Point Interface is a widely accepted roaming standard with initial funding from the EU.

The Open Clearing House Protocol is an alternative open roaming standard to OCPI.

5.4 Charging profiles and simultaneity factors

Network planning requires knowledge of electric vehicle charging profiles and simultaneity factors for different EV use cases. From a DSO's perspective, the EV **charging profile** is the charging behaviour of one specific CP throughout time. The **simultaneity factor** describes the probability of a certain number of charging points drawing their nominal power from the connection or network area at a given time. It is the key parameter for sizing electrical networks to cope with electric vehicle charging.

Charging profiles can either be obtained by recording charging sessions in pilot projects or by analysing general mobility data. Data availability is often limited, especially in developing countries. There are also publicly accessible tools for generating profiles, such as the Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite developed by NREL (Alternative Fuels Data Center, US Department of Energy, 2022).

When extrapolating data describing the current situation, reusing data from other sources or applying models from different regions, careful attention must be paid to the following aspects:

- Profiles differ per use case. Even at the LV distribution network scale, use cases are mixed. Datasets from public charging stations will show different characteristics than residential charging. Collecting data from residential users is intrusive and requires specific approaches (Wang, Du, & Jin Ye, 2020). Charging at work shows different profiles (Walz, Contreras, Rudion, & Wiest, 2020). The composition of different fleets and their specific profiles must be defined and translated into quantitative assumptions (Powella, Cezarb, Apostolaki-Iosifidoub, & Rajagopal, 2021).
- Profiles are influenced by behavioural patterns that may differ substantially by jurisdiction and geographical region. It must be verified whether existing datasets also apply to the situation of interest.
- Profiles may be influenced by tariffs, with and without managed charging technologies. Changes in pricing schemes will potentially change physical profiles (Mies, Helmus, & Hoed, 2018), (Bons, Hoed, Buatois, Geerts, & Schuring, 2020). Predicting users' response to (economic) incentive schemes requires dedicated attention in the modelling phase (Harbrecht, McKenna, Fischer, & Fichtner, 2018), (Desai, Chen, & Armington, 2018).
- EV profiles are only one aspect of the ongoing changes. The impact of electricity generation from renewables or demand response programmes may be more significant. Depending on regulations, these factors can also influence charging profiles (Andrenacci, Karagulian, & Genovese, 2022).
- In general, the current situation is subject to change, and the future may look quite different. For example, increasing EV battery capacity can result in longer but less frequent charging events.

NETWORK PLANNING – WHAT IS THE DESIGN CASE?

The design case for network planning is the highest load flow to be expected. For secure supply and reliable function, all assets have to be rated for this peak load, whether it happens twice a week or only once in 10 years.[13]

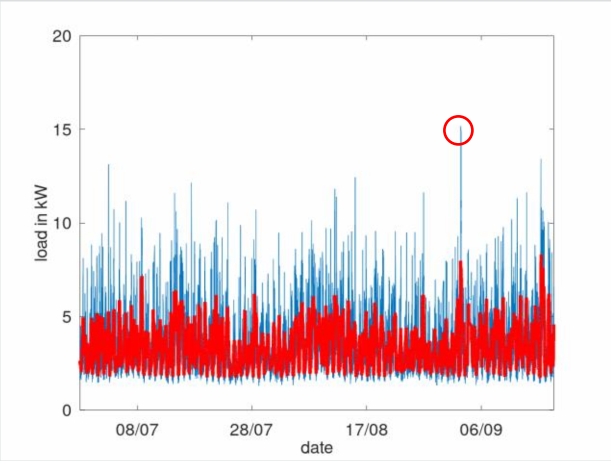


Figure 12: Cumulative load of 8 households; 10-minute (blue) and 4-hour (red) averages. Source: monitoring data from PVUpscale project, Amersfoort Nieuwland,(The Netherlands), 2000.

A very simplified example: The 4-hour average of the cumulative load of 8 households in Figure 12 is always less than 10 kW. The peak load (10-minute average) over this period is more than 15 kW. This single peak is the design criterion for network planning and asset rating.

At the distribution level, BEV **charging profiles** must be considered in context. Their mutual correlation and combination with other loads in the network determine the required peak ratings. An understanding of this correlation is a precondition for estimating simultaneity factors.

[13] Stationary batteries support flexibility and the optimisation of load flows but do not change this paradigm. They may help regularly, but their capabilities will incidentally be limited. These potentially rare but accountable situations make the option irrelevant for network planning.

Obviously, the **simultaneity** of a single EV charging point will be 100% each time a vehicle is charging. In a grid with two charging points, if only one of them is being used, the simultaneity at that time would be 50%. However, there is a chance that both charging points will be used simultaneously. The network planner must consider a maximum simultaneity of 100%.
With a growing number of EVs and, hence, charging points connected to a network section, the likelihood that all chargers will be serving BEVs at the same time decreases. This is even more true if the BEV charging and driving patterns in the area tend to vary (e.g. mix of residential and commercial BEVs).
The simultaneity of charging actions decreases with:

- More chargers,
- Higher charging capacity, i.e. shorter duration of the charging action;
- Diverse use case patterns in a network section.

The approach for calculating the simultaneity of BEV charging depends on the available data. Periodic adjustments should be carried out. At best, real-world charging profiles linked to the socio-economic status are regularly collected across a broad user group. Data privacy will have to be ensured. The generation of synthetic charging profiles can be a good alternative if real-world data is not available. At least the following parameters must be considered:

- **General mobility data:** Information on distance travelled, arrival/departure times and characteristics of the destination (e.g. home, work). This will make it possible to create individual vehicle travel profiles.
- **BEV parameters:** Battery capacity and consumption, resulting in the vehicle range.
- **Recharge preference:** How often an electric vehicle is recharged depends on the vehicle range and user preferences. Owners of a private residential charging station will have different charging patterns than users relying fully on the public charging infrastructure.

Figure 13 shows the simultaneity of low power charging per BEV based on German mobility data following the synthetic approach described above.

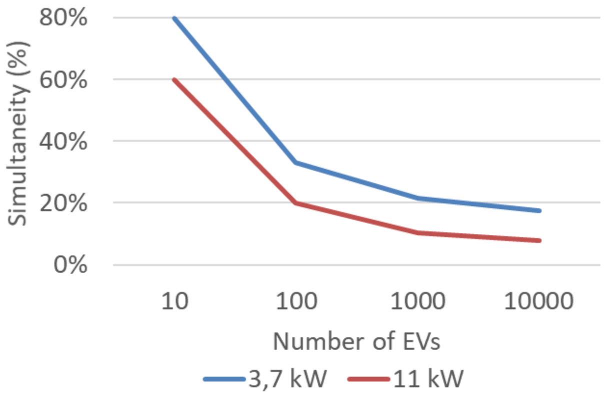


Figure 13: Simultaneity of EV charging for different charging power levels in Germany. Source: own elaboration.

METHODOLOGY FOR ESTIMATING SIMULTANEITY FACTORS

1. **Characterise areas of interest**
- Socio-economic differences
  - Early EV adopters are climate conscious (green & left-wing voters), interested in technology (younger age group) and sufficiently wealthy
- Mix of use cases / fleets in the area
  - EV type and daily usage determine energy demand
- Composition of charging schemes (private, public, office, supermarket, etc.)
  - Availability of private parking space and long-distance travel needs determine charging use cases and public charging infrastructure requirements

2. **Determine data collection strategy**
- Self-collection vs adjustment of international data
  - Self-collected data better reflects characteristics of the area of interest but requires higher effort
- Traffic vs charging data
  - Traffic data can be better adjusted to reflect future charging needs but is less accurate
- Monitoring vs surveys
  - Monitoring is precise but requires higher effort

3. **Potentially adjust data for future use**
- EV parameters
  - Battery size will most likely increase, thus reducing the number of charging sessions and increasing their length
- Connection behaviour
  - Ample recharging opportunities increase driver confidence to charge less often
- Managed charging
  - Network-compliant charging will reduce charging during peak network load hours
  - Energy price-based charging will increase charging during low-price hours

4. **Calculate simultaneity**
- Time-dependent number of charge points simultaneously charging EVs
  - Calculation methodology depends on the selected cases above. Individual calibration is necessary
- Network safety limit (confidence interval)
  - Set the permitted overload level, e.g. once every 10 years

In Figure 13, the simultaneity factors have been calculated with a confidence interval of 99.73%. The values can only be used as an estimate for residential BEV charging in specific networks. The planner will have to adjust for local mobility patterns. The simultaneity may be higher, especially in smaller grids where BEV users might have very similar charge profiles, e.g. charging at work.

The simultaneity factor not only decreases with the number of charging points but also as the charging power increases (e.g. 11 kW vs 3.7 kW) due to shorter charging sessions. However, the impact on the network is higher, which can be evaluated by multiplying the simultaneity factor with the charging power to obtain the average charging power per vehicle, as shown in Figure 14.

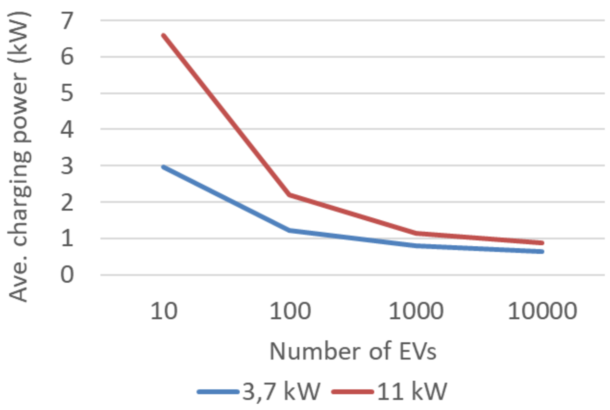


Figure 14: Maximum likely EV charging load per vehicle for different charging power levels in Germany. Source: own elaboration.

The expected likely maximum charging power per BEV charging point can be used to determine the necessary additional capacity of the network.

The general approach for the calculation of residential simultaneity can be applied to other EV charging use cases and network areas as well. For higher charging powers, a time-dependent evaluation might become necessary. For instance, in Germany, the power demand of highway chargers for passenger BEVs is expected to be highest on Saturdays during the summer holidays, corresponding to a peak in long-distance travel. This simultaneity will be close to 1.[14]

Simultaneity factors make it possible to assess the expected network impact of BEVs and adjust planning strategies accordingly. Since the simultaneity factor depends on the BEV parameters and charging strategy, regional and time-dependent differences can be observed.

DSOs are advised to monitor the electric vehicle charging simultaneity in their own network area. The best way to do so is to continuously collect the charging profiles from charge point operators or install their own measurement equipment. This data can then be used to determine the potential for managed charging and the need for network expansion. General data for network planners is still being developed. Since the level of additional network capacity highly depends on how much managed charging will be used in a network area (see Chapter 6.1 for details), it is difficult to provide clear recommendations on additional network capacity for BEV charging on a generalised basis. The German VDE Association for Electrical, Electronic & Information Technologies is currently working on recommendations for distribution system operators. This study was not yet available at the time this analysis was published.

5.5 Required infrastructure and communication

The simplest method to integrate electric vehicle charging into the grid is to implement strong network expansion at the low voltage level. However, this comes at a high price. For managed charging strategies, new infrastructure and planning requirements are necessary.

The following three-step approach has been identified as the most cost effective for network planners.

1. Modelling & monitoring
2. Managed charging
3. Network expansion

In the first step, visibility of the low voltage network should be increased, as it is typically very poor. Basic network and socio-economic data can be used in conjunction with power system modelling software to identify critical network sections where future BEV uptake may result in bottlenecks. The identified sections should be equipped with remote monitoring devices and integrated with existing systems. Devices with moderate uptime requirements compared to surveillance equipment for transmission networks are sufficient at the distribution level for cost-saving purposes.

In the second step, at the latest once an impending network shortage is imminent, the already established monitoring data should be used for the managed charging of electric vehicles. To do so, further infrastructure will become necessary, as explained later.

In the last step, network expansion will become necessary. Managed charging is only suitable up to a certain level of charging session adjustment. The tolerance level of the stakeholders (see Chapter 4.3) will depend on the pricing mechanisms, the socio-economic status and the country in question.

[14] Still, the overall impact on the power system and higher network levels will be moderate due to off-peak weekend operation.

Ideally, the described approach will ensure that the necessary infrastructure is only put in place once it is needed. The first two steps are typically skipped in practice, as regulation often doesn't allow for managed charging and incentivises network expansion.

For managed charging, the network loading status must be made available to the deciding entity. The transformers and power lines/cables to which the charging stations are directly connected must be equipped with monitoring devices, which typically require low voltage network monitoring. Data transfer is currently done via the mobile network or alternatives such as LoRaWAN, a radio frequency-based communication system. Powerline communication could also be used but might face issues on a large scale roll-out due to limited scalability.

In LV networks, the violation of voltage tolerances is regularly the limiting factor. Voltage data collection requires a more extensive measurement infrastructure and higher data transfer rates than load measurement collection. This choice, however, needs to be made on a case-by-case basis.

Data transfer security is essential, especially in a central approach. Malicious data falsification can potentially result in large scale blackouts. The same applies to billing data, although the malicious effect will be more harmful on an individual level. For this reason, several countries have developed safety and hardware standards. Data security and availability must be balanced, which is not always the case, as the example of the Smart Meter Gateway in Germany shows, where local network status data is very difficult to receive.

Apart from these essential requirements, further data processing might be necessary for use cases exceeding basic network safety. This may include EV status reports, such as the state of charge, arrival and anticipated departure time, in addition to residential or global energy requirements and prices. Availability will depend on the envisioned use/business case and the users' willingness to share private information. A trustworthy entity will have to be established in which the data is collected and processed.

There are different solutions to the question of which entity decides on whether the charging process needs to be adjusted. This decision can be made with a charger-centric, connection point-centric or car-centric approach. Each of these approaches has distinct advantages and disadvantages.

In a charger-centric approach, network status information or related instructions are sent to the charging station, which adjusts the charging power accordingly. The power profiles of other behind-the-meter appliances can be included as well to increase the utilisation of local PV generation.

In a connection point-centric approach, the network data is received by an energy management system that controls connected loads, including the EV charging process. The scope can be a single home, a business site or an urban community network.

Both approaches are fairly similar and will most likely coexist. A network connection point-centric approach is more suitable for environments with several controllable loads and generation. In contrast, a charger-centric approach is sufficient when EV charging is the main objective.

In contrast to the stationary approaches introduced above, the EV physically controls the charging process in a car-centric approach. A coordinating platform may connect networks and vehicles. The main advantage of this approach is that it is easier to access the vehicle data, such as state of charge and arrival time, in advance of the charging session, thus increasing plannability. In a car-centric approach, the available capacity of the expected charging location must be made available to the coordinating platform. So far, there are no common standards or platforms accepted by EV manufacturers and network operators on an international level. Additionally, data privacy concerns may arise.

Charger- and connection point-centric approaches are currently more common due to their simplicity and increased network operator control. Energy-based business cases are emerging following a car-centric approach propagated by EV OEMs. If these approaches coexist in the future, integrating them will be challenging.

From a DSO's perspective, the infrastructure deployment strategy will depend on the expected medium-term electric vehicle uptake. If a sufficient monitoring system is set up, the DSO can either apply an innovative approach or one that follows the market. For most DSOs, it will be sufficient to wait until commercial solutions have been tested in the field and adopt them accordingly once necessary. Some DSOs will have to take a more active approach if their network runs the risk of overloading before commercial solutions are widely tested. In this case, research institutes or innovative businesses are committed to quickly developing custom managed charging solutions.

5.6 Charging station registry

For consistent planning, development and monitoring of the network, the DSO requires up-to-date information on the location and type of installed mode 3 and 4 charging points, public, semi-public and private. (However, mode 1 and 2 charging locations cannot be tracked, charging just happens using the existing customer connections.)

In vertically integrated systems with only one DSO, such a database may be set up by the power system corporation; otherwise, regulators or transport authorities may do so. In countries with several DSOs operating their own databases, it will be beneficial to initially agree on the record structure and related information across the industry. To be complete, such a database has to be set up in an early stage of development.

PUBLICLY ACCESSIBLE CHARGING POINT REGISTERS

In any country with relevant e-mobility growth, you will find a register of public charging stations. Depending on the country's legislation, the information is collected, maintained and published by governmental authorities (Germany, United Kingdom) or independent non-commercial organisations (Norway). Alternatively, commercial CPOs/MSPs are required to make the information easily accessible (The Netherlands).

Generally, for each charging point, these registers contain geographical information, electrical parameters, number and type of connectors, as well as information about the commissioning date and the operator/service provider. Sometimes information about the actual status and the electricity providers is also included.

These public databases do not contain information on private chargers. They also abstract from the distribution network. For that reason, they may complement the DSO's databases but cannot replace them.

Registration of a charging point or station must be aligned with the connection approval process. The DSO designs and uses a standard connection application form to acquire all the relevant information, including at the very least geographical data (e.g. address), existing consumer connection, voltage level and power ratings, interface specifications (e.g. for managed charging and metering). In-house, the DSO completes this record with data on distribution feeder parameters, transformer ratings and loading. The correctness of the applicant's data must be verified by the technicians involved in the installation/commissioning, and this verification must be included with the application form.

Any attempt to register charging points after they have been installed runs a high risk of failure.

5.7 Network codes

Planning and operating power systems and networks are based on technical codes and provisions. The codes must address the specific challenges introduced by BEV charging.

Charging of BEVs combines aspects of loads as well as distributed generation. BEV chargers use power electronic converters. Their impact on load flows is substantial but can be controlled, and, in the case of V2G, they are associated with reverse power flows and behave like stationary storage devices. Hence, requirements for BEV chargers should be aligned and integrated with those for loads and distributed generators. This may also be a chance to update rudimentary and outdated requirements related to loads.

If not already covered by existing technical codes and standards, the following technical aspects must be addressed appropriately:

- Limitation of phase imbalances
- Limitation of harmonics
- Reactive power control and voltage support
- Active power control and congestion management

Given the high cumulative capacity of chargers installed in a power system, the provision of ancillary services such as frequency support may be considered, at least in the longer run. Again, there may be conflicting objectives (overloading of local LV networks, increased risk of unintended islanding). Potential adverse effects must be assessed carefully before implementing general technical requirements. Additionally, excessive requirements are a cost driver for CPs. The societal cost associated with advanced requirements must be balanced with their macro-economic benefits. Advanced requirements may result in higher hardware costs, leading to increased investments. This burden must be allocated fairly among the various stakeholders. These are policy choices.

Of course, DSOs have a vested interest in technical codes and standards supporting the safe and reliable operation of their systems. They must contribute actively to technical provisions at the earliest possible stage. Preferably, codes and standards are developed as a transparent and non-discriminatory stakeholder process. Staying close to existing (international) standards is desirable as it prevents the need to adjust equipment for national markets at an additional cost. Codes and standards must be reviewed regularly, e.g. every 2–5 years. This is the only way to guarantee consistency in a rapidly changing environment.

5.8 Key learnings for system planning

BEV charging must be accounted for during the planning stage. If a network section is going to be newly built or upgraded, the impact of electric vehicle charging throughout the network's lifetime must be accounted for during its construction. Preferably, DSOs will develop dedicated e-mobility network integration plans. Even with low BEV penetration, such plans provide a strategy for obtaining charging profiles, making it possible to assess future growth-related BEV network impacts.

The creation of regional simultaneity factors takes time and might also not be economically feasible for smaller DSOs. Until detailed data becomes available, approximate data from other regions can be used. In the case of regular network extension or reinforcement of underground LV networks, installing cables offering some extra capacity is advised. Construction costs are much higher than the cost of the cable itself. Installing spare capacity is especially justified in developing countries: electricity consumption will increase in addition to upcoming BEV charging.

A DSO needs a complete and consistent database of mode 3 and 4 charging points. This non-public DSO database is a registry of all public, semi-public and private chargers. Preferably, consistent data and record structures are defined nationwide. Charging stations must be registered during application procedures.

In existing network areas, monitoring equipment should be installed as the first step towards managed charging in areas where network congestions are foreseen. At a later stage the monitoring infrastructure can be upgraded to a managed charging system. Conventional network expansion might still become necessary once the managed charging solution affects the electric vehicle user to too high a degree.

DSOs must establish consistent technical codes and standards as a basis for the safe and reliable operation of their networks. These rules must at least cover basic network integration needs but ideally also provide the framework for future managed charging solutions. Network codes must be reviewed regularly and should anticipate likely future needs.

6 Distribution system operation

The efficient operation of distribution networks depends on the chosen planning approach. It is possible to steer charging processes using mandatory requirements or economic incentives. Adequate tariffing contributes to the optimised operation of distribution networks.

6.1 Flexibilities and elasticity

Managed charging is only possible to a certain level of stakeholder restriction, most notably the capability of the EV users to continue their journey. Studies have shown no impact on user satisfaction as long as managed charging is correctly applied and explained to the consumer (Western Power Distribution, 2019).

For this reason, managed charging is only suitable for charging sessions where the user is not actively waiting for the vehicle to finish charging, as is the case on road trips. Consequently, low power charging over an extended period offers the most flexibility. Fortunately, it matches the increasing need for managed charging in small (low voltage) networks (see Chapter 5.4). Available flexibility can either be used in a reactive or planned manner.

Reactive managed charging is only activated if monitored data from the network indicates that there is an immediate risk of network overload. Assuming that monitoring equipment is installed, the concept is quite simple to apply. The adjustment of power short latencies is crucial for safe application.

Planned managed charging optimises the charging sessions, for instance, to increase renewable energy consumption by matching the charging session with forecasted generation. Another use case is based on the expected future network load. However, future loading is difficult to predict in LV networks due to the limited number of connected loads. Stochastic evaluation is not possible. Private data, such as vehicle arrival and departure time, would have to be shared and made available. Data privacy concerns may arise. Due to potential planning errors, reactive managed charging algorithms must also be applied.

In general, the benefits of planned managed charging increase with the number of participants. Local platforms or markets can be formed to respond to electricity and network loading prices. With only a few participants, the availability of flexibility cannot be ensured. Moreover, there are risks related to market power and gaming.

From a DSO's perspective, reactive managed charging is necessary to ensure network stability. Especially at the lowest network level, the cable from the distribution transformer to the individual residential buildings, load forecasting is very difficult, thus making a reactive system necessary. Planning related charging strategies can be added as additional layers, even at a later stage.

6.2 Tariffs, pricing and incentives

Managed charging requires the participation of the involved stakeholders. Participation can be achieved either through mandatory requirements or monetary incentives.

Mandatory participation should be treated with caution, as it might negatively affect the perception of EVs. Additionally, it may result in increasing the proportion of uncontrolled invisible mode 2 charging at residential connections (Chapter 5.1).

Monetary incentives alone do not reliably ensure electric network stability due to the option of not participating. For the DSO, the option to control charging beyond the incentive scheme will be a precondition for supporting this approach.

Tariffs for managed BEV charging reflecting network needs must be sufficiently low compared to the regular tariff for unmanaged charging; otherwise, the effect will be limited. Significant tariff *reductions* imply that the default tariffs for unmanaged charging are high enough – otherwise, there is no room to offer a bonus. This may result in evading behaviour: users may tend to avoid CPs and charge at common wall sockets (mode 2) without managed charging facilities but with low power.

Existing low, possibly subsidised (residential) tariffs also send the wrong signal and stimulate mode 2 charging. Hence, the introduction of BEV charging tariffs may require the complete set of tariff schemes to be reviewed and adjusted.

A simplified alternative to flexibly adjusting charging power is a tariff component related to the time of use (ToU).

ToU tariffs contain valley and peak power prices, motivating BEV users to charge outside peak power periods. ToU tariffs will not reduce the simultaneity factor of BEV charging – the opposite may be true. The advantage from a network perspective is an improved combination with regular profiles related to other appliances, resulting in a lower overall peak load.

From a network perspective, tariff calculations are based on electricity demand patterns. Resource availability – i.e. energy prices – may be reflected as well. ToU tariffs may also reflect periods with a high share of renewable resources, such as solar PV. Still, such regulations must be applied carefully: if the generation of renewables does not run via the same LV network branches, these ToU components do not reduce local network loading, making them ineffective.

ToU tariffs are simple to apply. They require time-related metering (Chapter 6.3) but no additional managed charging infrastructure (Chapter 5.5). Quality and security of electricity supply cannot be ensured with these tariffs. Users might even use charging timers, available in every modern BEV, to start charging exactly once the valley tariff is activated. This behaviour may cause transient instabilities and power demands exceeding local network capacity (Western Power Distribution, 2019). Time-shifted ToU tariffs can eliminate this risk.

ToU tariffs can be an effective instrument, especially during the early adoption of e-mobility, until managed charging becomes necessary and in countries with limited ICT infrastructure. The impact and effectiveness of ToU tariffs should be monitored. Adjustments may be desirable over time. Preferably, such adjustments would not require (time-consuming) legal intervention.

The alternative to ToU tariffs is tariffs that respond dynamically to the distribution network situation. They assume the DSO's capability to adjust the charging power and the tariffing scheme, if necessary, in time and by location. The DSO should stipulate the maximum permissible intervention to not compromise user satisfaction. For instance, the maximum charging power reduction per day could be limited to *x* hours of *y* kWh. Additionally, the BEV user can be offered the option of requesting the maximum charging power for a specific charging session, as long as flexibility is still available (Western Power Distribution, 2019). Tariff design is currently being researched. The state of charge of the BEV battery can be regarded as a third parameter in addition to current electricity and network costs for the pricing as well as the decision of whether or not to charge.[15] Game theory can model the process up to any level of complexity.

In addition to electric vehicle tariffs, incentives for the construction and operation of charging stations capable of managed charging can be provided. For instance, Germany provided a €900 incentive for managed charging ready residential chargers (EnBW, 2022).

In order to influence BEV users to charge during off-peak hours, the total service fee must vary by about 150–300% between peak and off-peak hours.

DSOs can usually only influence the pricing structure of network charges, which is not sufficient to create the needed price spread. Policymakers must understand the importance of incentives that effectively support network-friendly BEV charging.

6.3 Metering and billing

Electric vehicle charging must be correctly metered and billed to ensure the confidence of EV users. Electric vehicle tariffs require a dedicated meter. Metering can happen in the BEV or the CP – in most jurisdictions, the CP is defined as the metering interface. A smart meter is necessary if flexible pricing is used, ideally with remote meter reading capability. The worldwide smart meter roll-out is still at an early stage but is currently accelerating.

Local authorities must ensure and regularly check that the meter is correctly calibrated. Metering of commercial DC charging is best done on the DC side to ensure that conversion losses are not billed. Measurement on the AC side with reduced rated transfer losses might be an alternative.

The billing of charging sessions requires a secure data transfer. The simplest method is physical annual meter reading by the electricity provider. This method is only suitable for private charging or if a CPO does not bill the charging session. The latter may be the case in shopping centres or hotels where clients may be offered charging for free. Otherwise, remote a billing infrastructure is required (Chapter 5.5) where the billed charging session to the end user covers several cost components:

- Generation/wholesale electricity prices
- Network costs
- Charging infrastructure costs
- MSP/roaming service fees
- Parking and reservation fees
- Taxes, levies

Electricity prices and network costs are typically based on consumption measurements. In many countries, the resale of electricity is prohibited. From a legal perspective, this applies to the transfer of electricity from the CP to the BEV. To avoid this ambiguity, regulations are adjusted to consider electric vehicle charging as a service. Otherwise, CPOs would have to bill based only on charging session duration. This option is sometimes also used to avoid metering altogether. Since it favours

[15] Currently, BEV manufacturers do not consistently offer the option to communicate SOC information to external parties.

electric vehicles with faster charging capabilities, it is gradually being prohibited by international regulations.

Charging infrastructure costs are billed by the CPO on an energy, power, time and/or charging session basis. Additional costs apply for the billing process and contract handling via the MSP and potential roaming partners.

With session fees (pay once you connect), there is no relation between the costs and the service provided (energy, time). In some jurisdictions (e.g. Germany), such fees are no longer allowed.

Time-related parking fees are regularly applied after a charging session to ensure that drivers vacate the charging station once the session is completed. Reservation fees are billed if a charging station is booked in advance of arrival to ensure availability.

Lastly, taxes and levies are added to all charging services based on country-specific regulations.

The billing process for public charging can be handled differently depending on the provider and the charging management system. Usually, the transaction is cashless, either through an ad hoc payment or a pre-existing contract. Ad hoc payments allow EV users to pay for a charging session directly by entering their payment information. If there is a charging contract, authorisation is done either via RFID (token and phone) or the vehicle itself (ISO 15118).

Charging contracts offer easier charging session transactions as long as the CPO accepts the MSP contract. If roaming is necessary, prices are often high, resulting in EV users having multiple charging contracts. Ad hoc payment decreases EV users' dependency on MSPs, but additional charging station investments are necessary. CPOs try to avoid these extra costs.

Metering and billing are less important for the DSO as they require no direct action. Typically, a dedicated governmental ministry will supervise that the equipment and infrastructure are calibrated correctly and sufficiently protected against data manipulation.

6.4 Integration with operational processes

So far, there is very little active operation of LV networks. With the roll-out of smart-grid concepts, preconditions are being created to change this situation – EV charging benefits from this trend.

Network operation can be organised in a centralised or decentralised approach.

In a centralised approach, all network and load flow related data is processed through the SCADA systems at the network operator's dispatch centre. The main advantage is increased data visibility and handling.

In a decentralised approach, necessary data is broadcasted directly from the local distribution transformer to the decision-making entity in a closed-loop approach. This approach matches a stationary decision-making process (charger- and network connection-centric approach). Data exchange is kept to a minimum, with only critical signals sent to the dispatch centre. Resiliency against wide-area failures and software attacks is increased. On the other hand, system-wide demand forecasting is not actively supported.

The network operator's operational processes must ensure the reliable transfer of the data. In addition to data safety and consistency (Chapter 5.5), data throughput and resilience are essential.

Most network operators have limited ICT infrastructure compared to the data requirements of EV charging. At least in the beginning, the decentralised approach can be advantageous. The future will tell since managed charging is still in its infancy. An introduction to several managed charging concepts and further readings can be found in (IRENA, 2019).

From a DSO's perspective, no direct action is required yet, apart from monitoring the system load and the availability of potential managed charging solutions. Once managed charging is applied, existing operational processes and interfaces at the DSO must be reviewed for compatibility with available managed charging solutions.

6.5 Key learnings for system operation

In the past, LV distribution networks were operated passively. Sensors and control capabilities are implemented at the MV or higher network levels. Operational procedures will have to be adjusted at the latest once managed charging of electric vehicles is introduced.

Immediate action must be taken to increase the DSOs' **knowledge of system loading**.

Visibility of network sections with high network loading and rising numbers of electric vehicle charging stations is increased by installing monitoring equipment. To apply managed charging, the monitoring equipment will have to be capable of sending data to the central or decentralised control unit. Multiple communication structures and operational processes are possible. The exact configuration will depend on the chosen commercial managed charging solution, stakeholder structure and related interfaces.

Depending on the current power system procedures, the following network overload mitigation strategies can be applied:

1. In many countries, residential customers already have the option or are required to use time-dependent electricity prices. These tariffs are especially common in vertically integrated power systems. In these cases, the energy provider and DSO already have experience with the necessary operational procedures of time-of-use tariffs (ToU), including time-dependent monitoring and billing. Establishing a ToU electric vehicle tariff will be relatively simple, at least from a technical perspective. Political support for these tariffs is necessary. The advantage of ToU tariffs for BEV charging will be a general reduction in peak network loading of existing network assets. The disadvantage is that the users' response does not reliably prevent peaks. Still, network reinforcement or managed charging might become necessary. If not set up correctly, the price incentive of a ToU tariff can result in additional costs for the DSO. ToU tariffs are useful at the beginning of BEV uptake but will face challenges later.

2. Load management is another option to reduce network loading. Load management systems ensure that protection limits are not violated. They reduce the individual peak load per network connection point compared to regular charging. These management systems are widely applied in power systems where an increase in the maximum permissible network connection power is either expensive or not allowed to the end customers. While load management is typically used for fleet charging, solutions for residential customers with one or two BEVs exist as well. The main advantage of load management is that commercial solutions already exist and are being installed to save peak power costs with little further incentive from the DSO. The main disadvantage is that load management cannot ensure network stability since the power network is not designed to handle the simultaneous maximum power draw of multiple network connection points at the same time, which will become the case as the number of electric vehicles increases. Load management systems are still useful for network load reduction and should be encouraged by DSOs, especially at the beginning of the electric vehicle uptake.

3. Managed charging will become necessary to keep network investments at acceptable levels. Large-scale commercial application is not yet established. DSOs keep track of market developments of managed charging solutions. If necessary, they support policy design and development related to managed charging. The DSO's right to control a charging session in the event of network overload is crucial. User participation may be mandatory or incentivised economically. Newly built charging stations should be capable of receiving or processing externally, e.g. in the case of network overload. Charging stations with OCPP or EEBus communication protocols provide such interfaces. Charging stations capable of managed charging are more expensive than basic charging stations. Options to trigger the necessary extra investments include monetary incentives (offered in Germany) and mandatory requirements. Typically, the DSO is not directly responsible for establishing these policies.

7 Key action points for embracing EV charging as a DSO

This chapter provides a list of the key action points for integrating electric vehicles into the distribution grid based on the information established in the previous sections. The aim is to highlight the steps a DSO needs to take in order to be prepared to integrate rising proportions of electric vehicles into its system. Special attention is given to low-cost solutions that can be adopted quickly.

DSOs face growing electric vehicle network integration challenges and are already establishing the necessary environment, even if electric vehicle adoption is still relatively rare. Some of the main steps a DSO must take to integrate electric vehicles into its network are:

1. **Review country-specific information**
2. **Adjust policy to support EV charging**
3. **Apply fast and easily adaptable solutions**
4. **Establish managed charging**

Action can be taken simultaneously depending on the speed required to ensure safe integration. Based on the tasks listed above, which are explained in the following chapter, the distribution system operator has the right tools to ensure that electric vehicles are integrated successfully into the network. Nevertheless, the network integration of electric vehicles is still in the early stages of development. Therefore, it is the responsibility of each DSO to continuously update their strategy and integrate new learnings, either from their own system or drawn from international experience.

7.1 Review country-specific information

Direct action is required to develop an understanding of the current electric vehicle network integration strategy of the country in question. Depending on the situation, the action points of the following subchapters should be adjusted to suit the necessary action for the successful inclusion of electric vehicle charging into the distribution network. Country-specific information should include at least the following:

1. Review existing policy and regulations
2. Check internal load connection procedures
3. Gain knowledge of current network capacity
4. Analyse electric vehicle market development
5. Check the availability of managed charging solutions

7.2 Adjust policy to support EV charging

Public policies must support network-compliant electric vehicle charging. The DSO must use its influence to ensure that the following aspects are included in the regulations as soon as possible for the given purpose. Even if not directly needed, policies should anticipate necessary provisions due to long update cycles. Suggested policy amendments are as follows:

1. Technical rules to limit the impact of BEV charging on the security and quality of the power supply (including aspects such as phase imbalances, harmonics, voltage, etc.)
2. The right to withhold a network connection from charging stations until network bottlenecks are dissolved
3. The right to establish contractual agreements with mobility service providers to temporarily reduce charging power in the case of network overload
4. Sufficient funding for DSOs to:
    a. Take into account the rising network load of electric vehicle charging in newly built network sections
    b. Integrate managed charging solutions into the existing network
5. Incentives or mandatory requirements for charging stations, used in cases where the charging session can be delayed without affecting the user to prepare for managed charging
6. Electric vehicle charging tariffs compatible with network security
    a. Time-dependent charging tariffs
    b. Tariffs that provide the network operator with control

7.3 Apply fast and easily adaptable solutions

Fast and simple solutions enable DSOs to stay on top of the electric vehicle network integration challenge. As soon as possible and as long as the regulation allows for, the DSO should establish the following routines:

1. Ensure charging stations that fulfil minimum technical standards to reduce their impact on phase imbalances, harmonics, voltage and frequency.
2. Register all charging stations with the DSO providing at least the location and maximum charging power per outlet.

3. Potentially only allow the installation of charging stations with a rated power of 11–50 kW in case it is capable of receiving managed charging signals. Whether or not the restriction is necessary depends on the available network capacity.
    a. Currently, charging stations offering the OCPP or EEBus protocol are capable of receiving standardised managed charging signals.
    b. Potentially even lower limits can be used in networks with little remaining capacity.
    c. Electric vehicle charging above 50 kW is considered unsuitable for managed charging. At these fast charging rates, the electric vehicle driver is usually waiting for the charging process to finish.
4. Offer a dedicated electric vehicle time-of-use tariff if the network operator already has experience with time-of-use tariffs.
    a. Time-of-use tariffs are especially useful at the beginning of electric vehicle development; they must be established quickly.
    b. The price spread between peak and valley prices should be 150–300% (the exact values depend on customers' sensitivity to prices).
5. Update network planning routines for newly constructed electricity networks to support electric vehicle charging throughout their lifetime.
    a. Use international charging data to determine the network load increase in the case of seldomly used managed charging (max. 3% of the time).
    b. Establish charging session collection routines to base planning routines on local data in future.
    c. For all installations where construction or reinforcement work is expensive compared to the cost of materials (e.g. underground cables), calculate the necessary network capacity with future electric vehicle charging and build the network infrastructure accordingly.

7.4 Establish managed charging

In most power systems, managed charging that reacts to DSO network overload signals is necessary to integrate large numbers of electric vehicles. The DSO should use the international BEV market development and the current network capacity to determine if an innovative or market following approach is needed. For MENA countries, a market following approach is most likely sufficient. The main difference is that managed charging solutions do not need to be developed in-house. Regardless of the managed charging development approach chosen, the distribution system operator ensures the following once managed charging becomes necessary:

1. Establish the required communication infrastructure to obtain measurement data and send control signals to the charging stations.
    a. The communication structure will depend on the available commercial solutions and already existing infrastructure at the DSO. A universal solution has not yet emerged.
2. Offer the charging station operator an electric vehicle charging tariff, potentially together with the energy provider.
    a. Standalone tariff components managed by the network operator alone will most likely be used in unbundled power systems.
    b. In the future, only limited charging power (e.g. up to 6 A per phase), which is not controlled by the DSO, may be available. Charging above the limit will be mandatorily controlled by the DSO.
3. A managed charging solution is needed, which at the very least reacts to network overload signals. Planned or energy-centric charging methods can be added as additional layers to reduce total power system costs.
4. Vehicle-to-grid or -home may become useful for the large-scale integration of renewable energy. From a local network perspective, it is not needed and is often even counterproductive. Once these solutions are commercially available, the DSO will have to ensure that network safety is not neglected.

Based on the action points introduced above, the distribution system operator has the right tools to ensure that electric vehicles are integrated into the network successfully. In the end, it is the responsibility of each DSO to update their strategy continuously and integrate new learnings, either from their own system or drawn from international experience

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List of abbreviations

BEV	Battery electric vehicles
CP	Charging point
CPO	Charging point operator
DSO	Distribution system operator
EMS	Energy management system
EVSE	Electric vehicle supply equipment
HEV	Hybrid electric vehicles
HV	High voltage
ICCB	In-cable control box
ICE	Internal combustion engine
LV	Low voltage
MSP	Mobility service provider
MV	Medium voltage
TCO	Total cost of ownership
ToU	Time of use
V2G	Vehicle to grid

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